Forward Tracking and Vertexing;
physics case, challenges and detector design

CLIC09,

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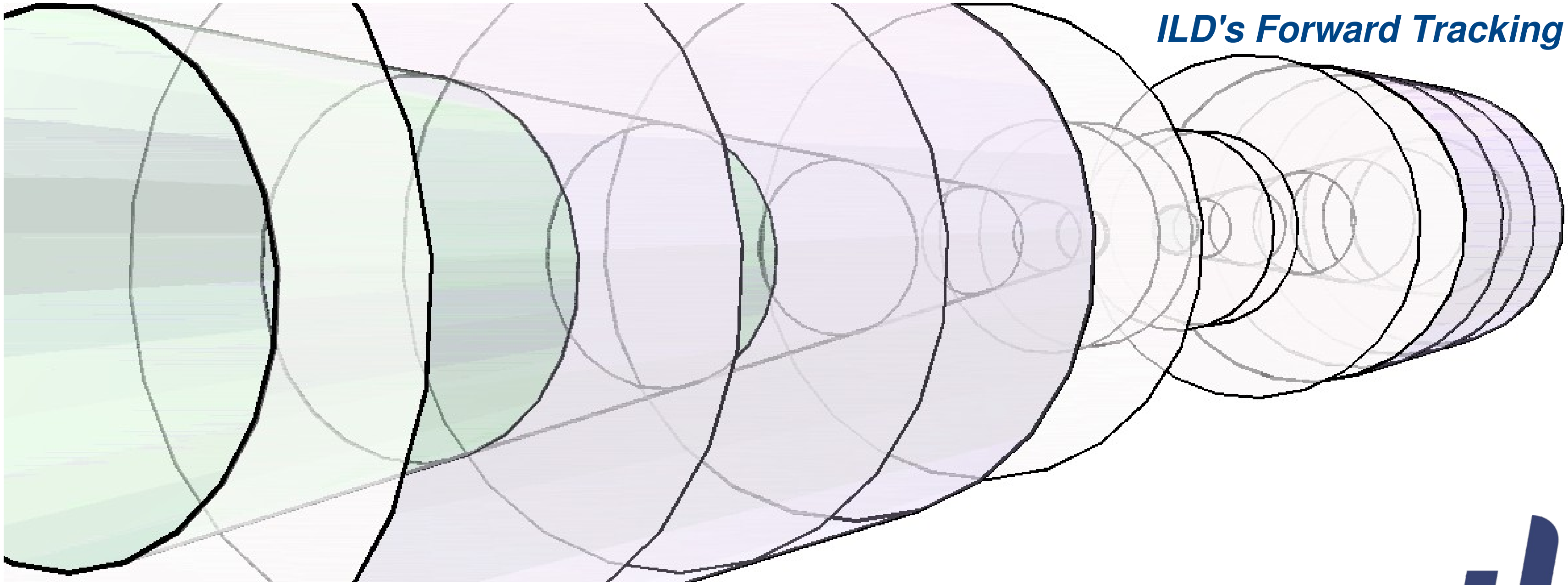
Marcel Vos (IFIC – U. Valencia/CSIC)

The scope of this talk



ILD's Forward Tracking Disks

The forward region = $6^o < \theta < 30^o$

(0.1 rad < θ < 0.45 rad, 0.9 < cos θ < 0.995, 1.5 < | η | < 3)

in future e^+e^- colliders

The physics case

Why is forward tracking performance important?

There is a series of very relevant physics processes where final state particles are predominantly emitted at small polar angle

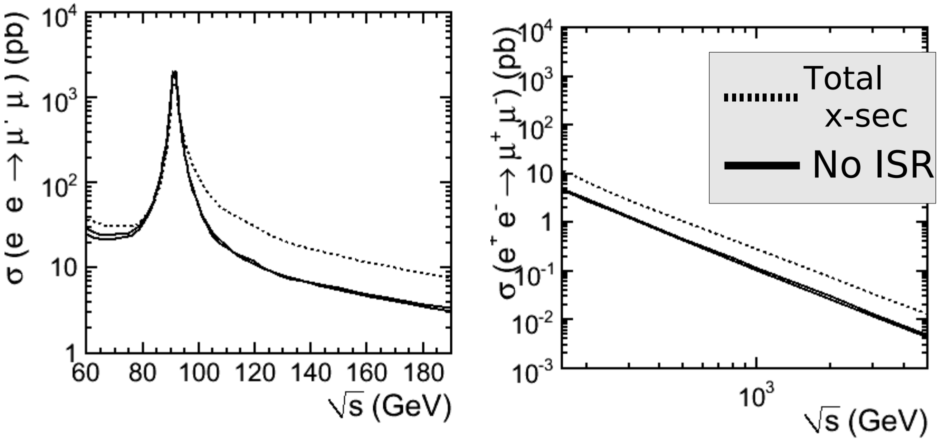
Mostly electrons, but also muons, t, b- and c-jets

Marcel.Vos@ific.uv.es

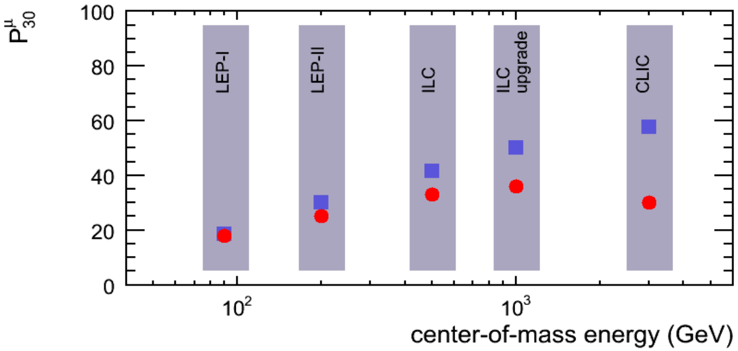
From LEP-I to the ILC (to CLIC)

$e^+e^- \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$

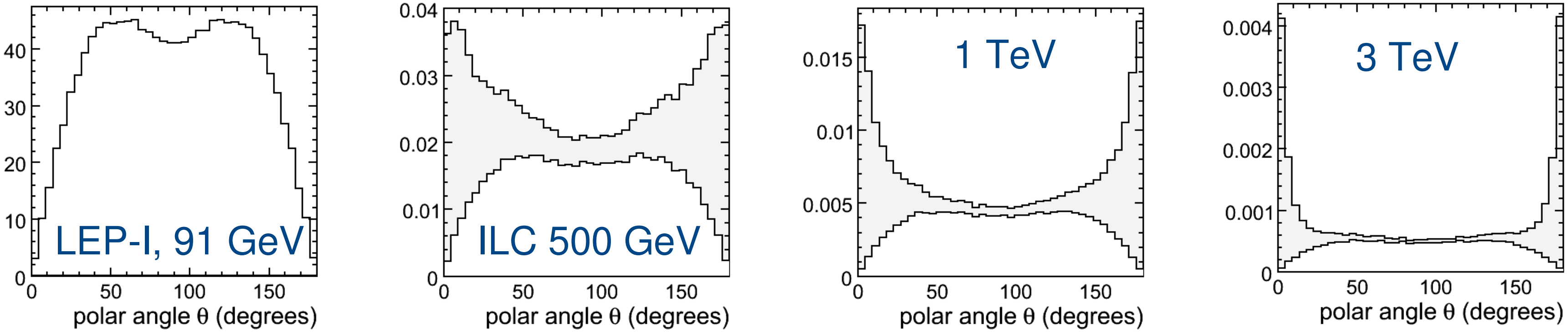
with(----)/without(——) ISR



P^X_{30}: Probability that final state product X is emitted at a polar angle $5 < \theta < 30^\circ$



Determine the relevance of the forward region in several key processes for a number of scenarios increasing center-of-mass energy

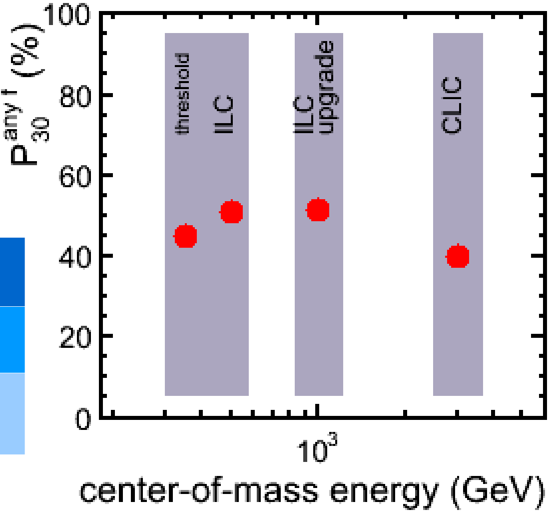


Multi-fermion final states

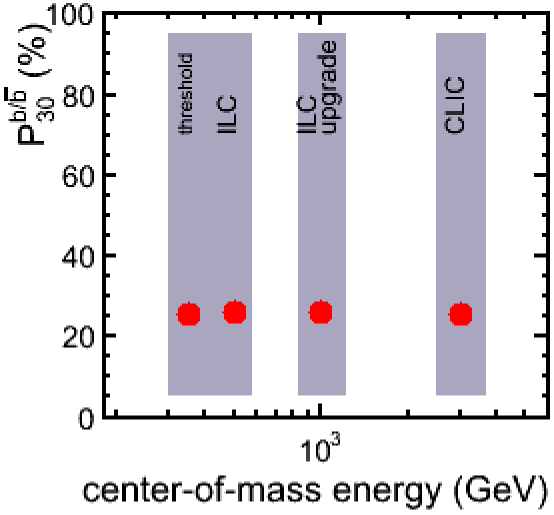
- **2 → 2 processes dominated LEP-I physics**
- **At larger $\sqrt{s}$, 2 → N, with N=4,6,8,... becomes more relevant**

$\sqrt{s}$	91 GeV	500 GeV	3 TeV
machine	LEP-I	ILC	CLIC
$\langle N_{jets} \rangle$	<3	5	6.4

At least 1 (of 6) fermions



At least 1 (of 2) b-quarks



As an example look at e^+e^- → Z → tt, no ISR

$\sqrt{s}$	*500 GeV*	*1 TeV*	*3 TeV*
at least one top	0.15	0.17	0.22
at least one b	0.22	0.25	0.25
any fermion	0.59	0.51	0.4

Final states with many fermions (like ordinary SM tt-events) are hardly ever fully contained in the central detector

Tag a forward b-jet in 1 out of 4 events: requires vertexing

Top as a window on new physics: A_{FB}^{tt}

LC has a sensitivity to Z' resonances with masses that are well beyond it's direct reach due to interference of γ/Z/Z' .

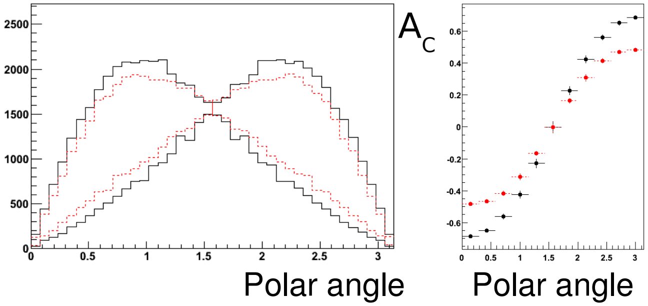
Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV
ee --> tt Cross-section	91.7 ± 0.1	88.2 ± 0.2	93.8 ± 0.2	94.9 ± 0.2	94.9 ± 0.2
A_{FB}^{tt}	0.41 ± 0.01	0.296 ± 0.007	0.390 ± 0.007	0.395 ± 0.007	0.398 ± 0.006
$A_{FB}^{tt\,(central)}$	0.36 ± 0.01	0.263 ± 0.007	0.346 ± 0.007	0.352 ± 0.007	0.351 ± 0.007

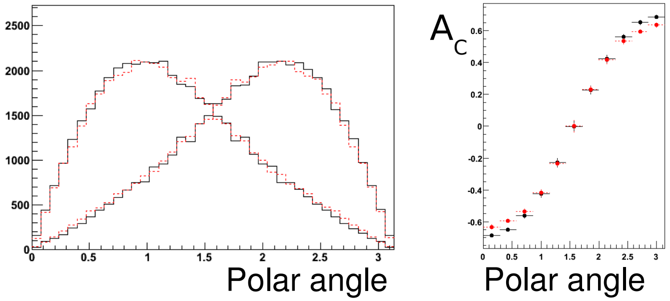
LO production cross-section (MadGraph) and top quark FB asymmetry for the ee--> tt process in the Standard Model and various sequential Z' scenarios. Errors are purely statistical, assuming 500 pb^{-1}.

Forward backward asymmetry is a very sensitive probe

Not only A_{FB}^{tt}, but also A_{FB} of b from tt, A_{FB} of μ from tt

A forward signal by construction: the (exact) center of the detector does not contribute



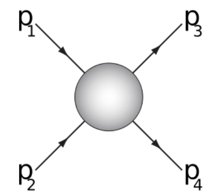


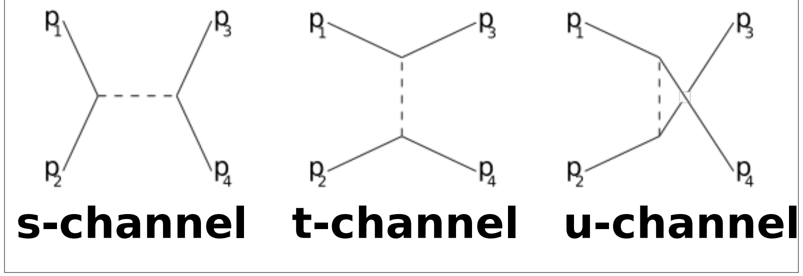
The importance of the t-channel

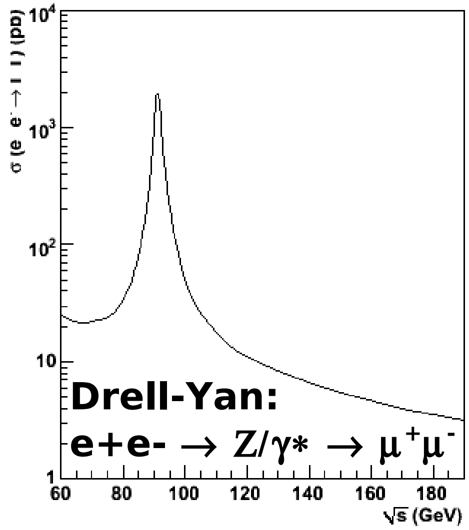
With increasing center-of-mass energy
(from LEP-I to to LEP-II to ILC to CLIC)
the importance of the t-channel increases

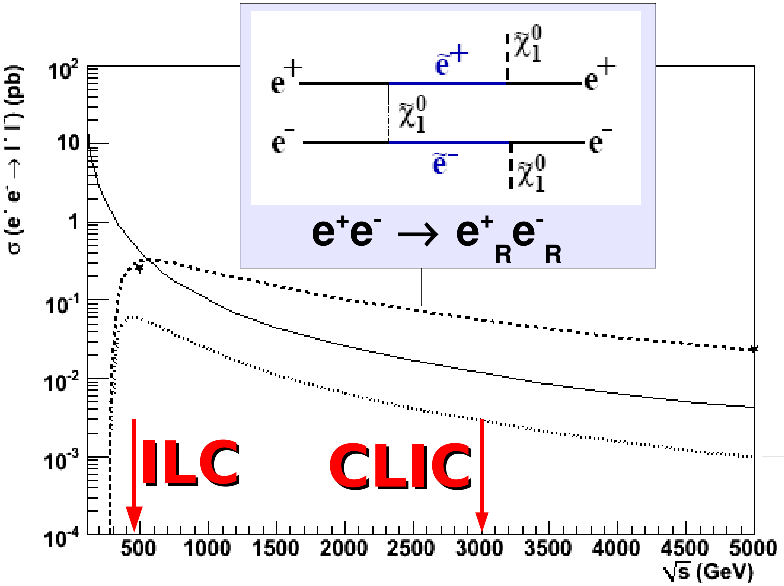
Example: scalar lepton production in SUSY (SPS benchmark point 1a)

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

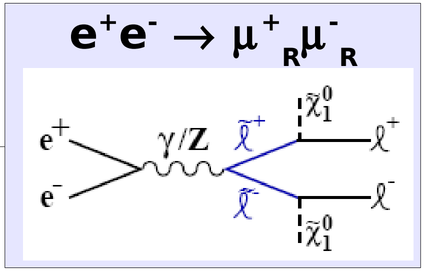






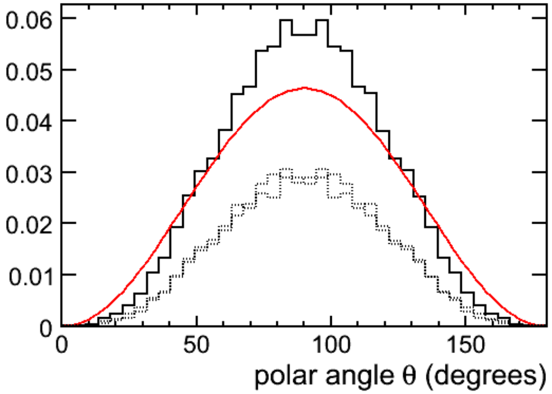


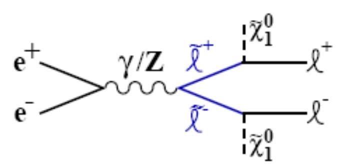
MadGraph/MadEvent (hep-ph/0208156)



The importance of the t-channel

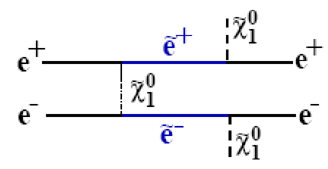
polar angle distribution for s-lepton production

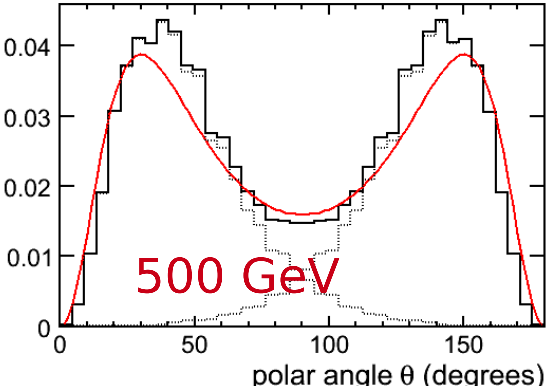


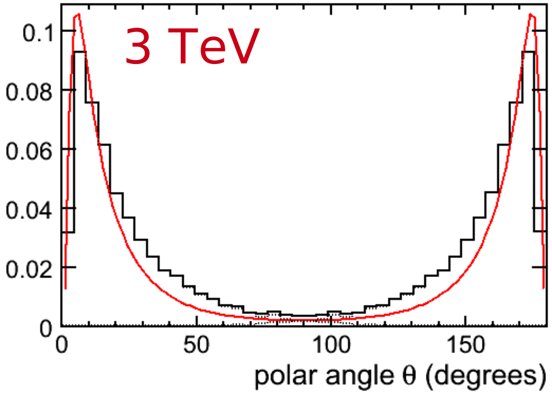


scalar muons

s-electro







Products from t-channel prefer the forward region, and this feature becomes more pronounced at CLIC energies

Fraction of forward s-electrons (θ < 30°) for s-electron pair production in SPS1a

@ 500 GeV 24 % @ 1 TeV 50 %

Scan SUSY space (analytical expression for polar angle distribution)

t-channel

$P_{e\sim}^{30}$ for scalar electron production in different machines and for different points of the Snowmass benchmark set

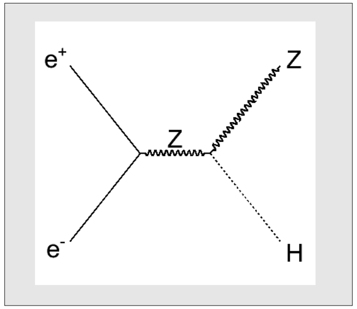
	$m\ (e_R)$	*$m(\chi^0)$*	*500 GeV*	*800 GeV*	*1 TeV*	*2 TeV*	*3 TeV*
SPS1a	*135*	*99*	30	46	54	70	73
SPS2	*1451*	*79*	-	-	-	-	10
SPS3	*178*	*160*	20	38	48	63	70
SPS4	*416*	*118*	-	-	21	65	72
SPS5	*192*	*119*	21	47	57	70	71
SPS6	*236*	*189*	8	27	38	64	73
SPS7	*127*	*161*	25	35	43	65	73
SPS8	*176*	*137*	24	44	47	66	72
SPS9	*303*	*175*	-	26	42	61	67

Scalar electron production is extremely peaked in the forward direction whenever the center-of-machine exceeds the masses of the s-electron and neutralino significantly.

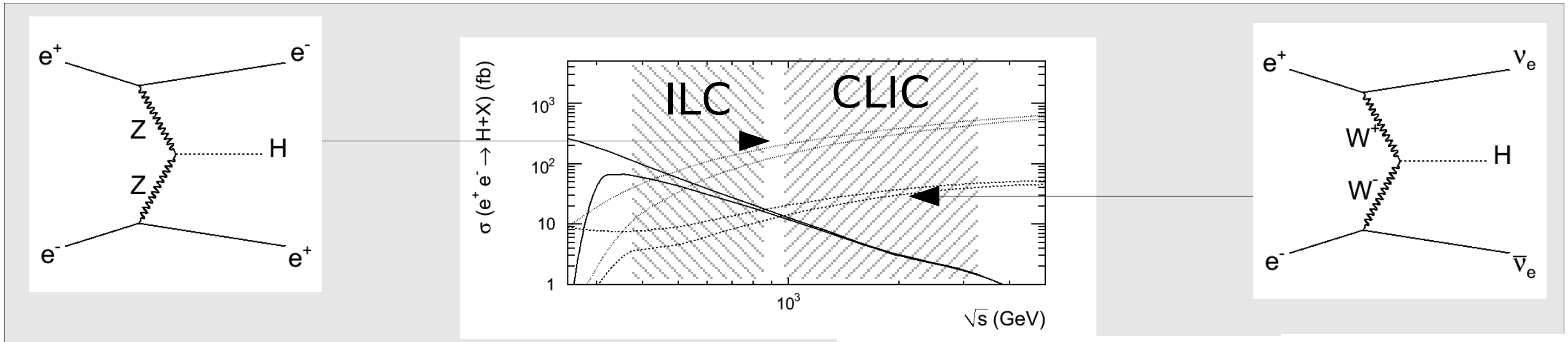
Further high-mass SUSY points from post-WMAP catalogue
H' , m_{eR} = 433 GeV , m_{X0} = 402 GeV, P = 42 %
K' , m_{eR} = 1114 GeV, m_{X0} = 573 GeV, P = 17 %

Very preliminary!

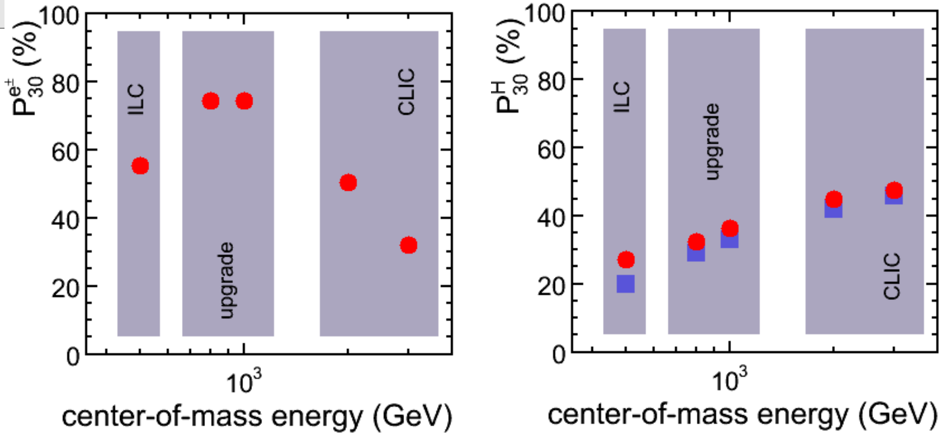
Higgs production



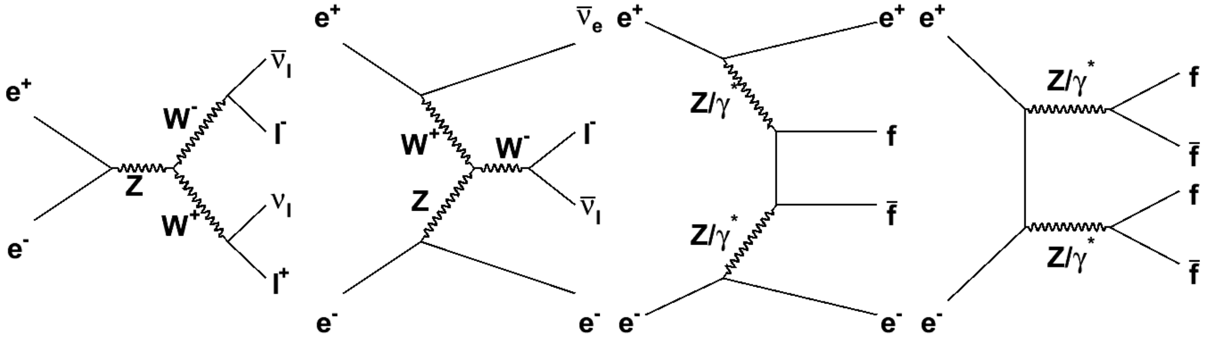
- Higgs-strahlung is the dominant Higgs production process for a low-mass at small √s
- Recoil-mass reconstruction is the tracking benchmark analysis par excellence
- A very central signature



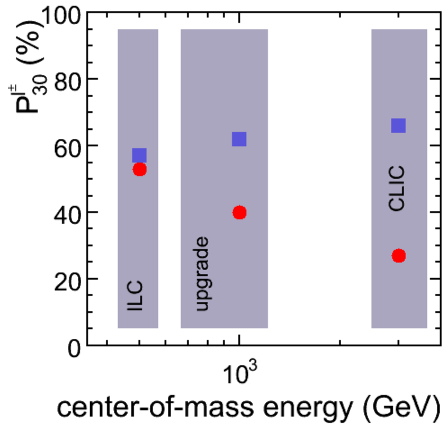
Vector boson fusion processes are much more interesting at CLIC
ZZH can be reconstructed using the recoil-mass analysis on extremely forward electrons

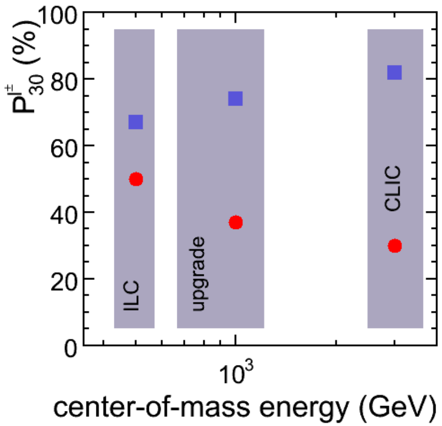


Di-boson production



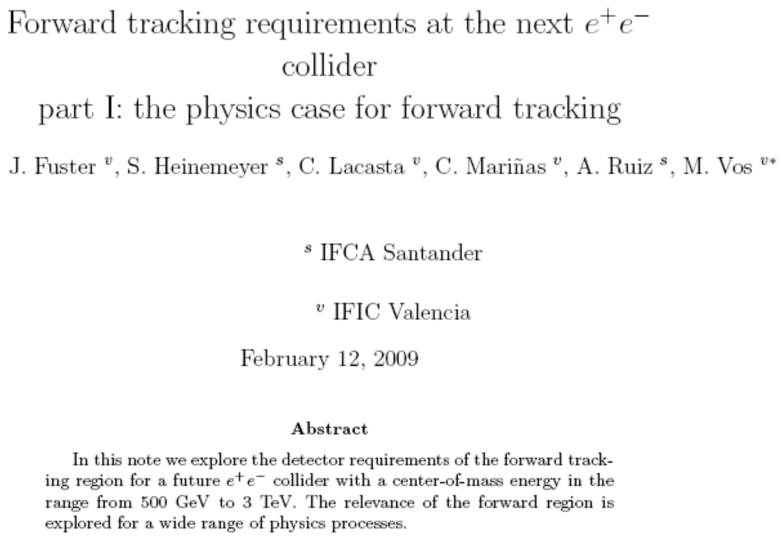
The last example: di-boson production.





The polar angle distribution of electrons is extremely peaked in forward direction

Forward tracking physics case



Forward tracking requirements at the next e^+e^- collider
part I: the physics case for forward tracking

J. Fuster [v], S. Heinemeyer [s], C. Lacasta [v], C. Mariñas [v], A. Ruiz [s], M. Vos [v*]

[s] IFCA Santander

[v] IFIC Valencia

February 12, 2009

Abstract

In this note we explore the detector requirements of the forward tracking region for a future e^+e^- collider with a center-of-mass energy in the range from 500 GeV to 3 TeV. The relevance of the forward region is explored for a wide range of physics processes.

Little guidance for forward detector design from standard benchmark reactions ($\cos\theta < 0.95$)

Together with many other analyses and channels that we didn't discuss:

- A_{FB} in the bb and cc system
- Degenerate staus and neutralino
- center-of-mass energy determination using $\mu\mu\gamma$ events

These examples make the physics case for orward tracking:

At a high-energy e^+e^- collider several potentially very interesting physics analyses require excellent tracking and vertexing performance. These arguments become more urgent as the center-of-mass energy increases. Precise electron reconstruction is of particular importance.

Why is forward tracking challenging?

The material!
Hermetic coverage
Significant background at smallest radii
The unfavorable orientation of the magnetic field
Abundant low momentum tracks – pattern recognition

Material budget: an analogy

With all technological advances (Moore's law) we should be able to produce better cars than 60 years ago...

Citroen 2CV, 1949
A 375 cc engine yields 8 horse power and a top speed of 65 km/h.
Weighs ~ 500 kg
Consumes 4.4 l/100 km

Material budget: an analogy

And we are...

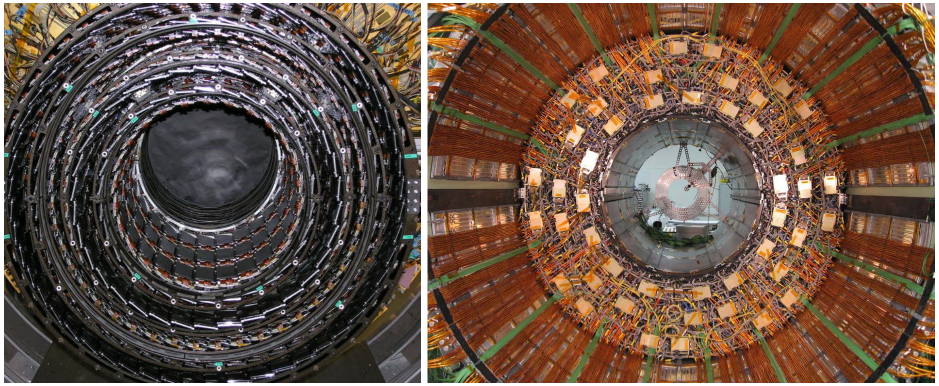
Centaurus (U. Minnesota)
2.5 - 3 horse power to reach 65 km/h.
Weighs 190 kg
Consumption: 0 on a sunny day

Material budget: an analogy

... but we can also take the technological advantage to improve other specifications. (we cannot push ALL specs to the limit!)

Audi Q7
280-350 horse power
top speed 248 km/h.
Weighs 2240 kg
Consumes: 10 l/100 km

Material budget: the LHC



The CMS tracker seen from the interaction point (TIB, leftmost figure) and from the calorimeter (TOB, rightmost figure)

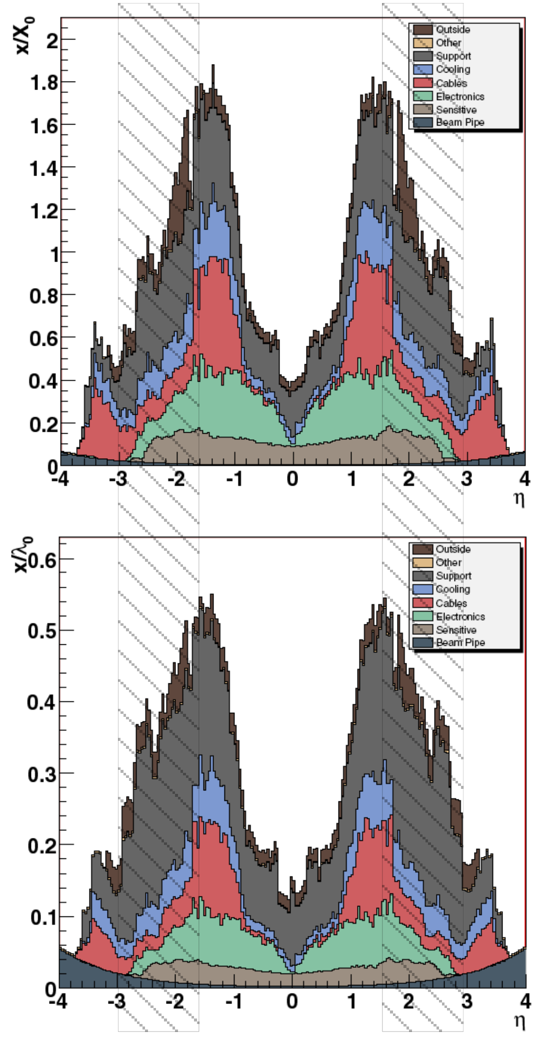
- 30 % X_0,10 % λ_0 in central region

  sensitive, **support** and **electronics**
- 180 % X_0 50 % $\lambda_0$in transition region

  add services: **cooling** and **cables** (power)
- 100 % X_0, 35% λ_0 on edge of acceptance

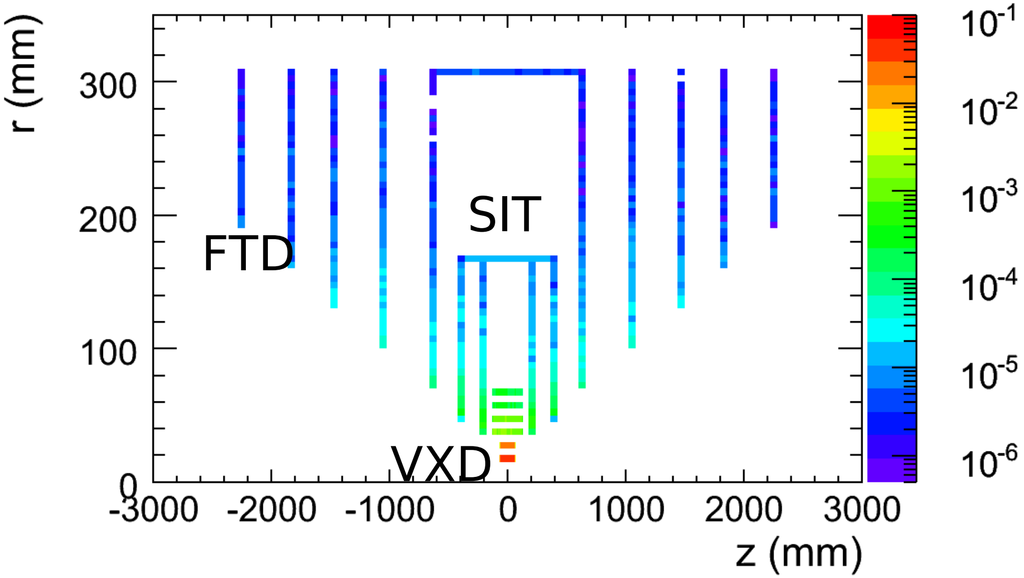
  ($\eta = \pm 2.5$)

Clearly, not good for EM calorimetry..., but even tracking efficiency for anything but muons is limited by the material. Even if the material is not a particular problem of the forwar region, it typically is worst there...



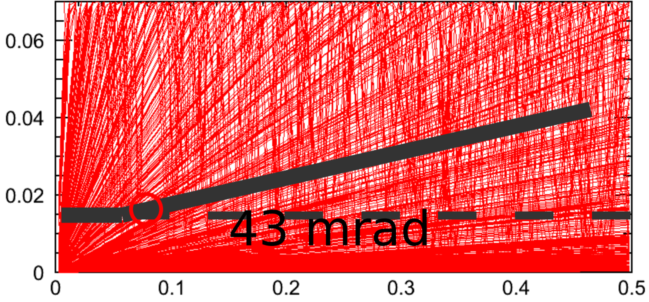
Figures from R. Ranieri, CERN-CMS-CR-2008-007

Pair background



ILD GEANT4 simulation of GUINEA-PIG events by Toni Harlin
(thanks also to A. Vogel and Katarzyna Wichman)

Beamstrahlung in ILC (GuineaPig + helix in 5 T field)



Hit density in ILD (#/mm^2/BX)

detector	min	typical	max
VXD 1		4×10^{-2}	
VXD 6		3×10^{-4}	
FTD1	$<10^{-5}$	1×10^{-4}	2×10^{-3}
FTD7	5×10^{-6}	7×10^{-6}	9×10^{-6}
SIT 1		3×10^{-5}	
SIT 2		3×10^{-6}	

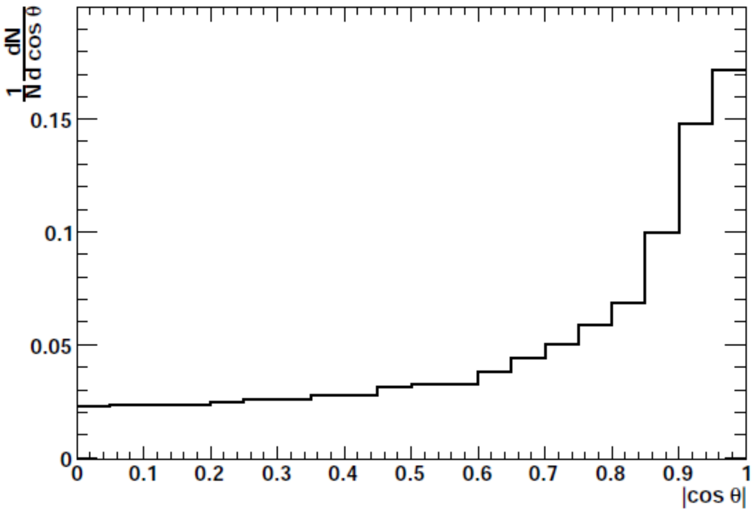
Hit density = number of GEANT4 energy deposits per unit area per ILC bunch crossing

Hit density drops by several orders of magnitude from R=1.5 cm to R =6 cm

	Typical area sensitive elements	*time resolution LC:*
pixel:	25 x 25 μm^2 = 6.25 x 10^{-4} mm^2	100 BX
strips:	50 μm x 10 cm = 0.5 mm^2	1 BX

Never underestimate a good micro-strip detector!

$\gamma\gamma \rightarrow$ hadrons



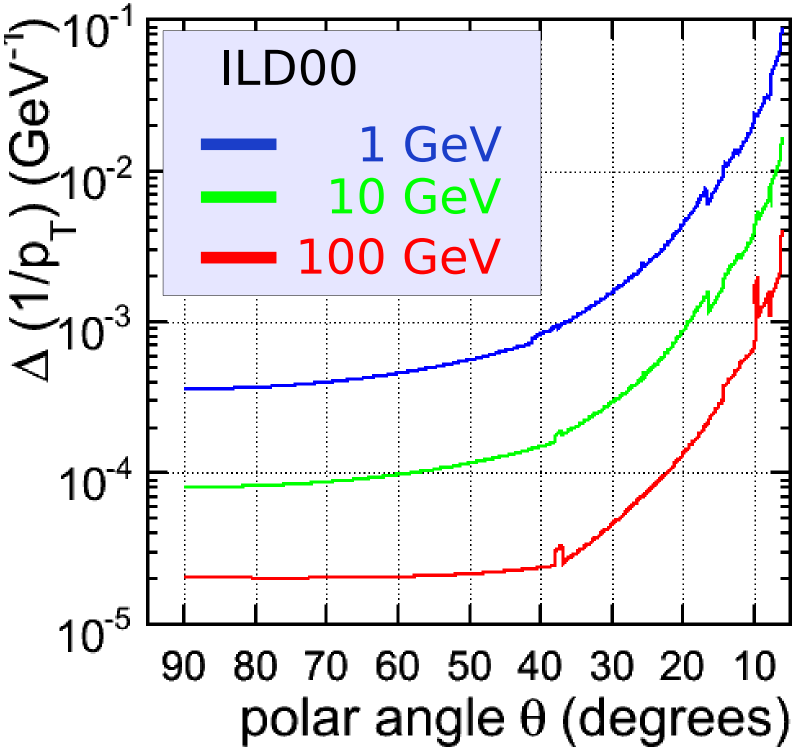
From M. Battaglia, J.J. Blaising, J. Quevillon, CLIC note in preparation

An average of 22 charged particles is produced by $\gamma\gamma \rightarrow$ hadrons in each CLIC bunch crossing
Harder to beat this background by moving out to larger radius (typical p= 100s of MeV to several GeV)
Very forward distribution (factor 10 compared to central region)

Momentum resolution

ILC tracking specification: momentum resolution $\Delta(1/p_T) < 5 \times 10^{-5}$ (GeV^{-1})

Precision required to reconstruct the Higgs boson using the recoil method, and to reconstruct SUSY end-points



ILD00 momentum resolution single muons

- ✔ Performance ~ stable down to 36°
- ✔ Steep loss between 6-36°

worse forward performance is the result of a combination of

(a) magnetic field orientation (inevitable within 4π detector geometry)

(b) loss of # of measurements in TPC

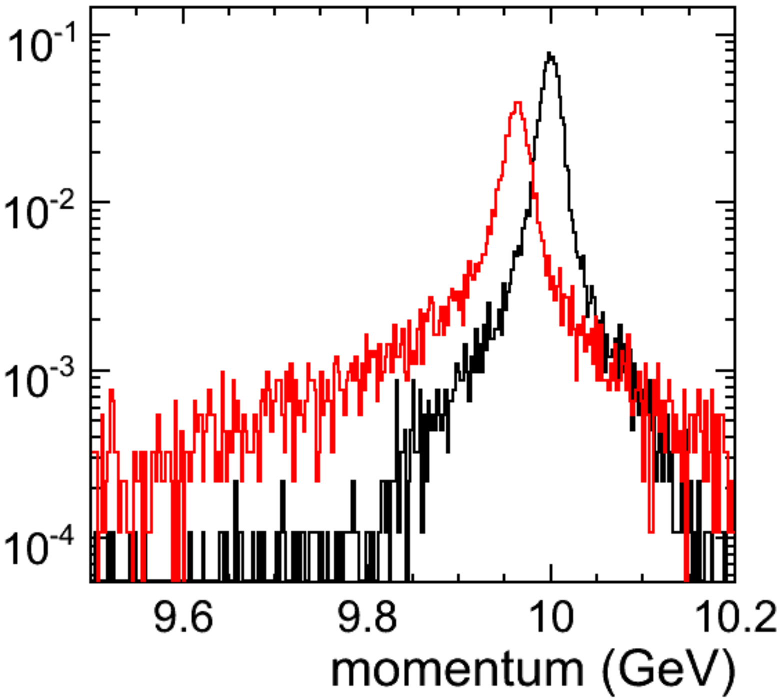
Momentum resolution

Momentum resolution for electrons (remember t-channel!!)

- ✔ Ongoing study (Jordi Duarte, IFCA): generate single-electron samples (private, but available for those interested)
- ✔ compare tracker-only momentum resolution of single electrons with the LOI results for muons
- ✔ Understand tracker-parameter dependence
  - ➔ material!

ILD00 full simulation

▬ 10 GeV μ^-
▬ 10 GeV e^-



Ongoing study by Jordi Duarte

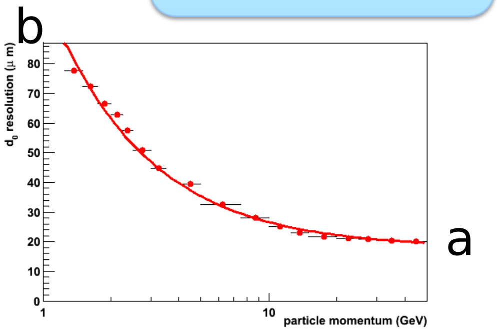
Impact parameter resolution

VXD: impact parameter resolution 5 – 10 µm.

This precision is required to achieve excellent heavy flavour tagging, particularly for couplings of the Higgs boson to charm (cτ ~150 µm) and bottom (cτ ~ 450 µm)

	a (µm)	b (µm GeV)
LEP	25	70
SLD	8	33
LHC	12	70
ILC	5	10

$$\sigma_{IP} = a \oplus \frac{b}{p\sin^{3/2}\theta}$$



Unprecedented precision
(small pixels, 20x20 µm^2)

Strongly reduce the multiple Coulomb scattering term
(material: 0.1 % X_0 / layer ~ 100 µm Si)

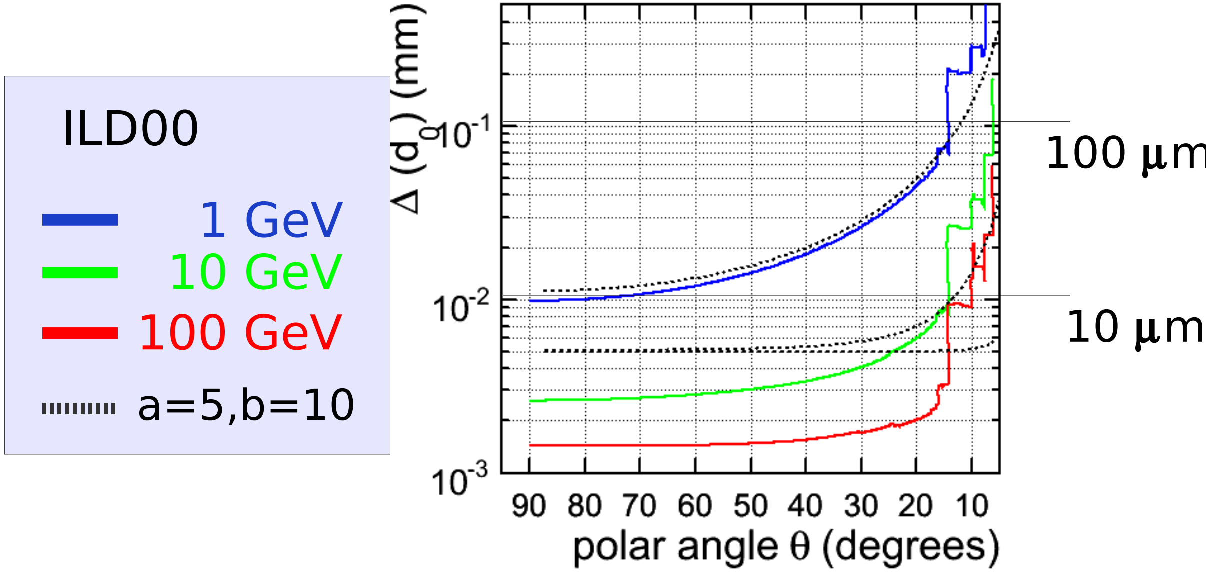
ILD vertexing performance

central:

a~1.7 µm

forward:

performance significantly worse than extrapolation of barrel formula with a=5,b=10

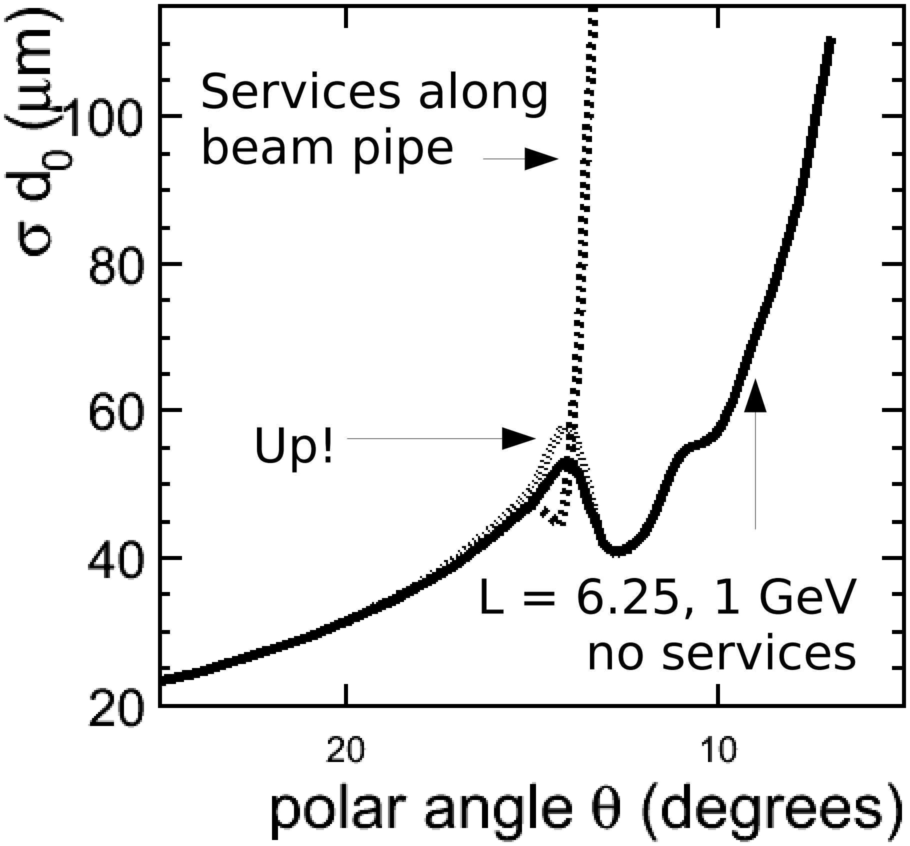


Routing the barrel VXD services

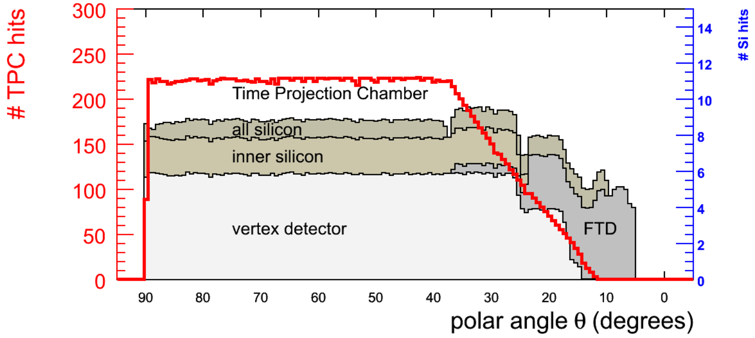
Toy model for barrel+end-cap vertex detector
For details see A. Ruiz, ALCPG Albuquerque

The forward region clearly does NOT like the services routed along the beam pipe

If anything close to a few radiation lengths comes in the way between endcap and interaction point we can forget about forward vertexing



Pattern recognition



Clearly, 6-15 degrees is weakest region in ILD in terms of number of measurements. And remember:

- non-negligible pair background
- First disks close to interaction point (jets!)
- Abundant low-momentum tracks (loopers)

Ongoing study (Carmen Iglesias) Evaluate hit densities in tt events per disk and per petal (subdividing disks in 8,20 or 16 single-wafer segments)

- Average #hits/disk falls by a factor 3 due to reduced angular coverage of outermost disks
- Average #hits/petal falls even faster (outermost disks divided in 16 segments)

It is important to evaluate the hit density locally (jets)

- A significant probability to receive several hits/petal remains even in the outermost disk

	#hits/disk		#hits/petal	
disk	avg.	peak	avg.	peak
FTD1	9	37	1.1	12
FTD2	5	27	0.6	10
FTD3	8	36	0.4	10
FTD4	6	29	0.3	9
FTD5	5	25	0.3	10
FTD6	4	23	0.2	5
FTD7	3	28	0.2	4

Pattern recognition

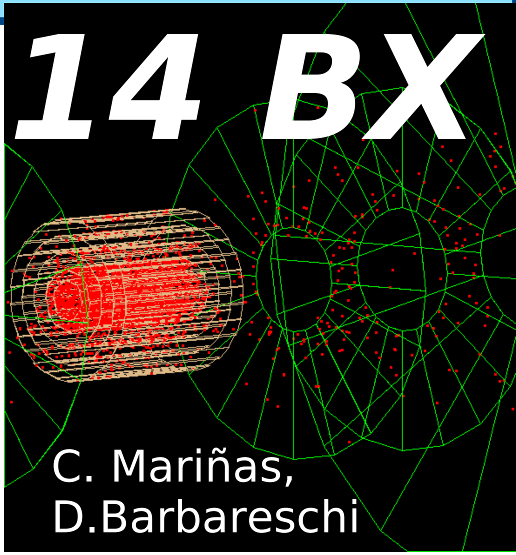
The combinatorial algorithm on stand-alone FTD is able to efficiently and cleanly reconstruct tracks down to a p_T of 100 MeV, provided:

R-segmentation: in innermost disks 500 μm required, in outermost disks O (1cm)

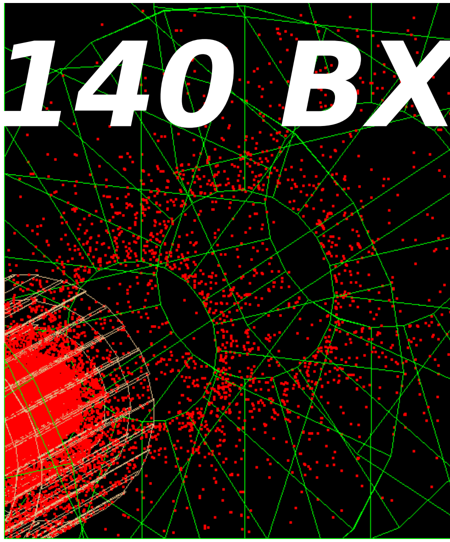
Read-out speed: beyond several 10s of integrated bunch crossings the density of low momentum tracks prevents algorithm convergence

Material: an increase of the material beyond 1%/disk has dramatic consequences on pattern recognition

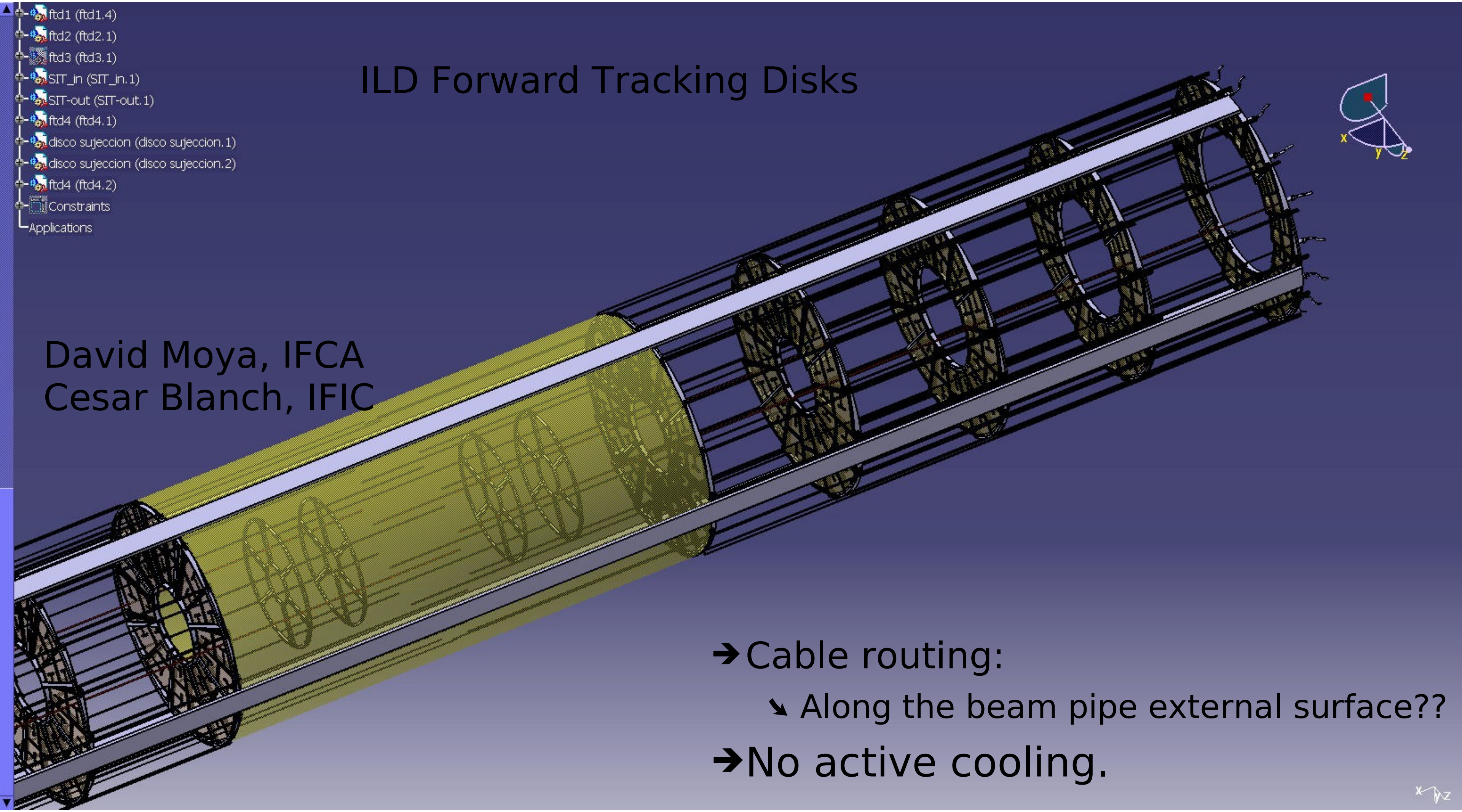
(see M. V., ILC meeting Sendai)



C. Mariñas,
D.Barbareschi



Working out a detailed design



ILD Forward Tracking Disks

David Moya, IFCA
Cesar Blanch, IFIC

- ➔ Cable routing:
  - ➘ Along the beam pipe external surface??
- ➔ No active cooling.

Conclusions

There is significant physics to be gained (or lost) in the forward region (6-30º)

- ISR (return-to-the-Z)
- Many-fermion final states
- t-channel production of new light objects
- Vector boson fusion Higgs production
- Vector boson pairs

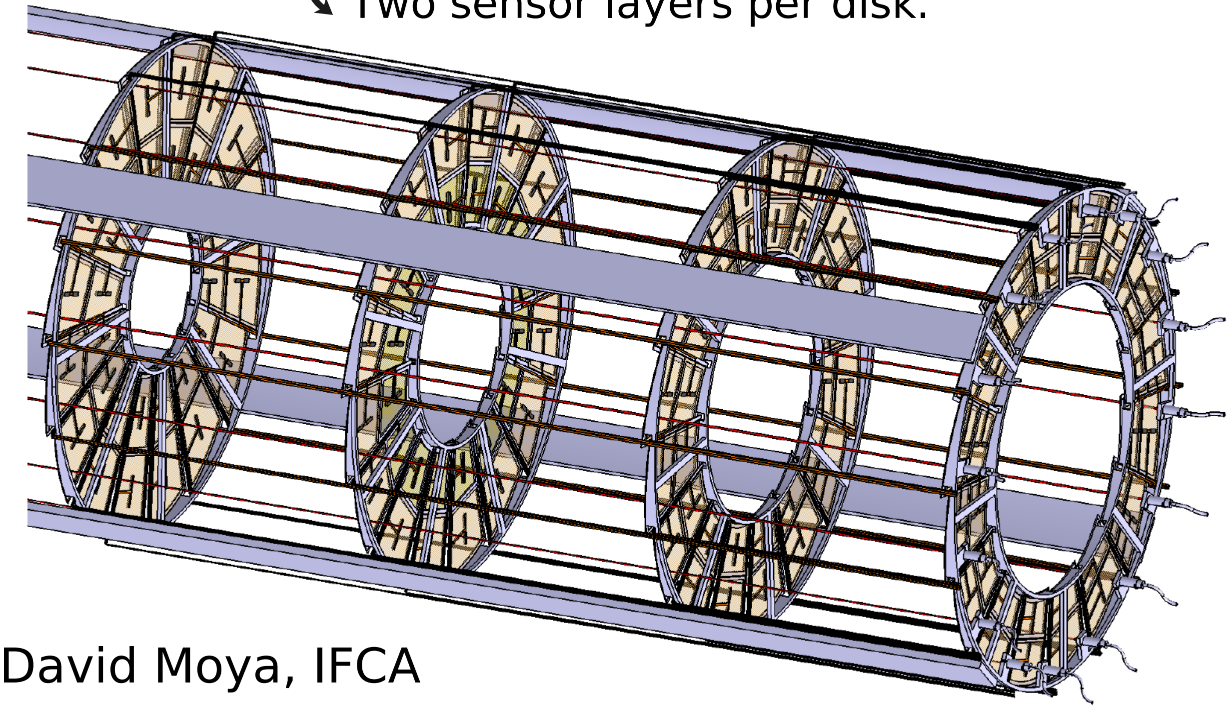
If the central tracking and vertexing is somewhat of a challenge, maintaining good performance at small polar angle is close to impossible

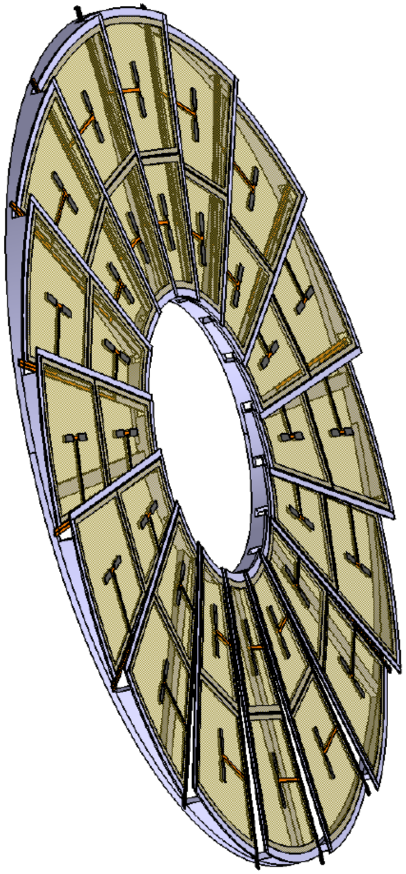
- Material
- Backgrounds
- Momentum resolution (B-field)
- Vertexing (barrel services)
- Pattern recognition

Backup slides

Towards an FTD design

- ➔ Micro-strip module guidelines:
  - ➘ ROC on sensor
  - ➘ ROC thinned to 50-100 um
  - ➘ 6” wafers (approx 10 cm x 10 cm sensors)
  - ➘ 150 μ m thickness
    - ➘ Two sensor layers per disk.





David Moya, IFCA

Conclusions

Interest of the forward region:

in several interesting physics cases the final state products have a strong preference for the forward region

Specific challenges:

momentum resolution under unfavorable field orientation
impact parameter measurement for very forward tracks
non-negligible background level (read-out speed)
standalone pattern recognition (background, low p tracks)
minimal distortion of particles/global performance

Requirements:

granularity @ reasonable speed staying within the power budget

Laser alignment:

the only “many-layer” silicon system in ILD

Towards a design:

engineering studies of FTD

More information on
http://ific.uv.es/~vos/ilc

REFERENCES

A. Savoy Navarro et al. (the SiLC collaboration), PRC review, DESY, 2008

A. Savoy Navarro et al. (the SiLC collaboration), ILC tracking review, Beijing 2007

The challenges of forward tracking, *invited talk*, IEEE NSS&MIC, Dresden, Germany, 2008

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Overview of SiLC simulation, Linear Collider Workshop (LCWS07), *DESY (Germany), 2007,* arXiv:0801.4509

The SiLC simulation task force, ILC software workshop, Orsay, France, 2007

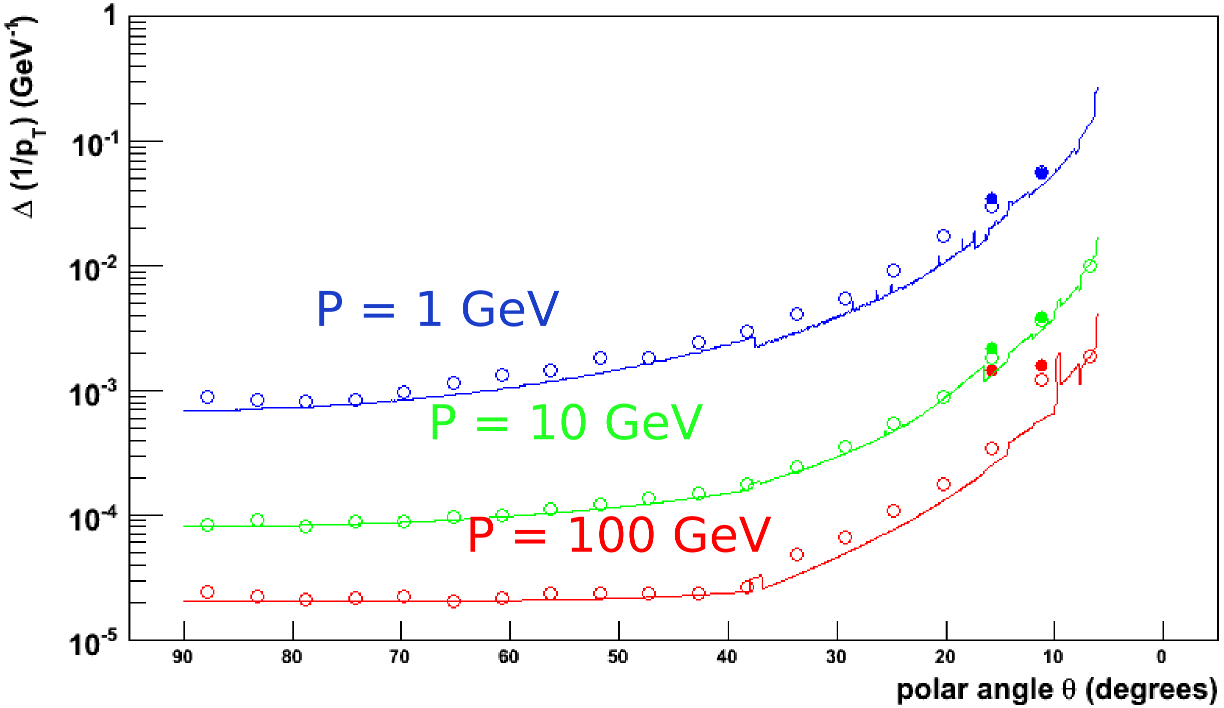
The SiLC simulation task force, Tracking review, "the SiLC collaboration",, Beijing, China, 2007

Transverse momentum resolution versus polar angle
Measured on three single-muon samples with fixed |p|

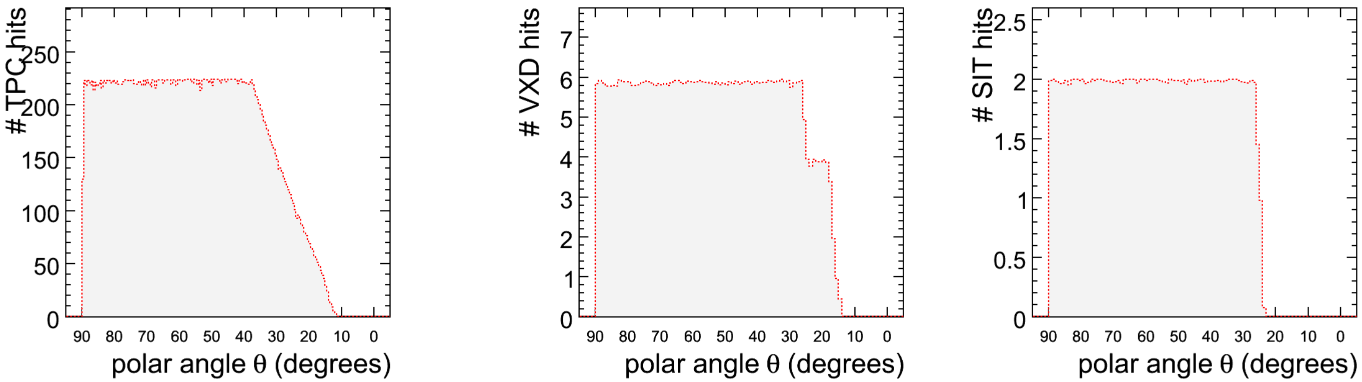
— LiCToy on ILD00 (full KF fit), *M. Valentan, HEPHY Vienna*

○ FullLDCTracking on ILD00 (Mokka/MarlinReco) *Vos/Duarte/Iglesias*

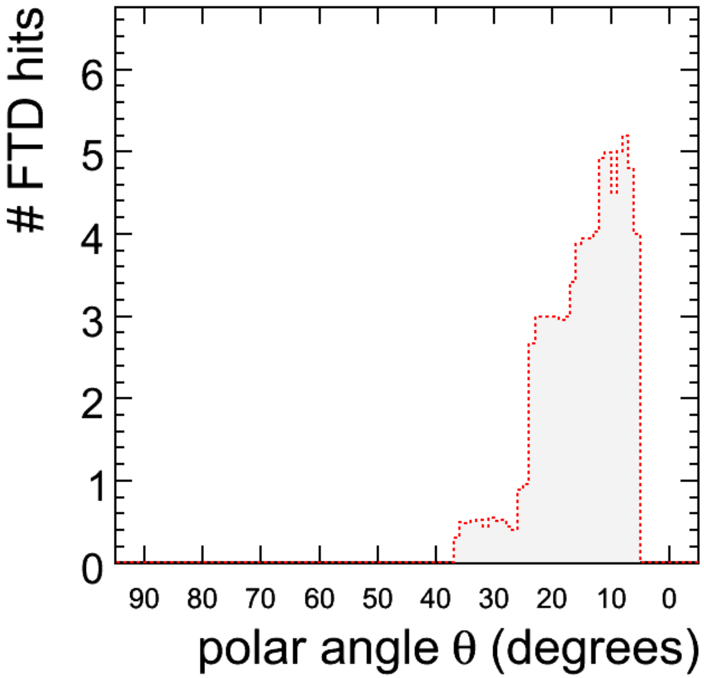
● CMS KF Track Fit on standalone FTD *Vos/Duarte/Iglesias*



Coverage



Concept	Magnetic Field	Angular Coverage	
		5-point	3-point
SiD	5 T	12.5 (43 barrel)	9
LDC	4 T	26	19
GLD	3T	26 (6 points)	18 (4 barrel + 2 disk)
ILD	3.5 T	26 (6 points)	17



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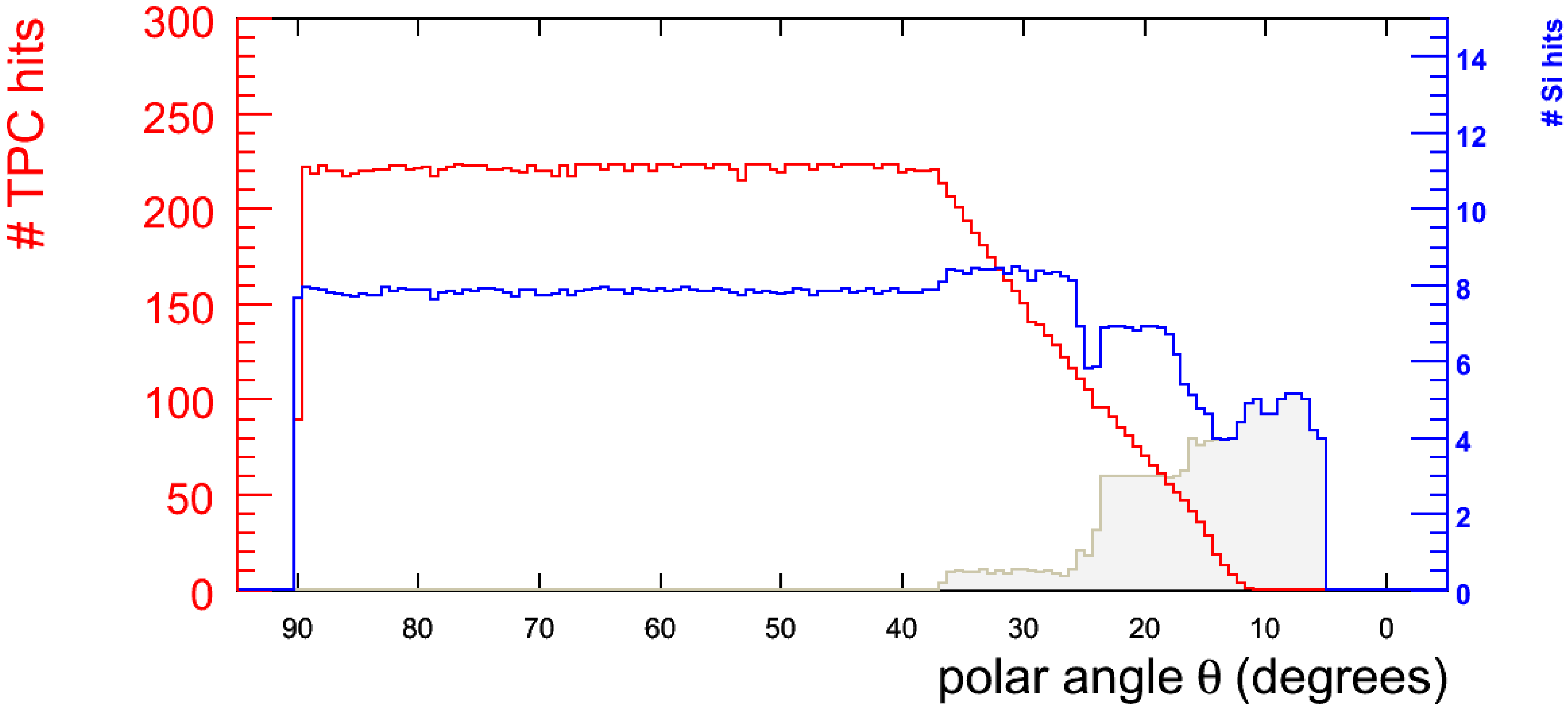

TPC hits
300
250
200
150
100
50
0
Si hits
14
12
10
8
6
4
2
0
90
80
70
60
50
40
30
20
10
0
polar angle θ (degrees)

Transverse impact parameter resolution versus polar angle
Measured on three single-muon samples with fixed |p|

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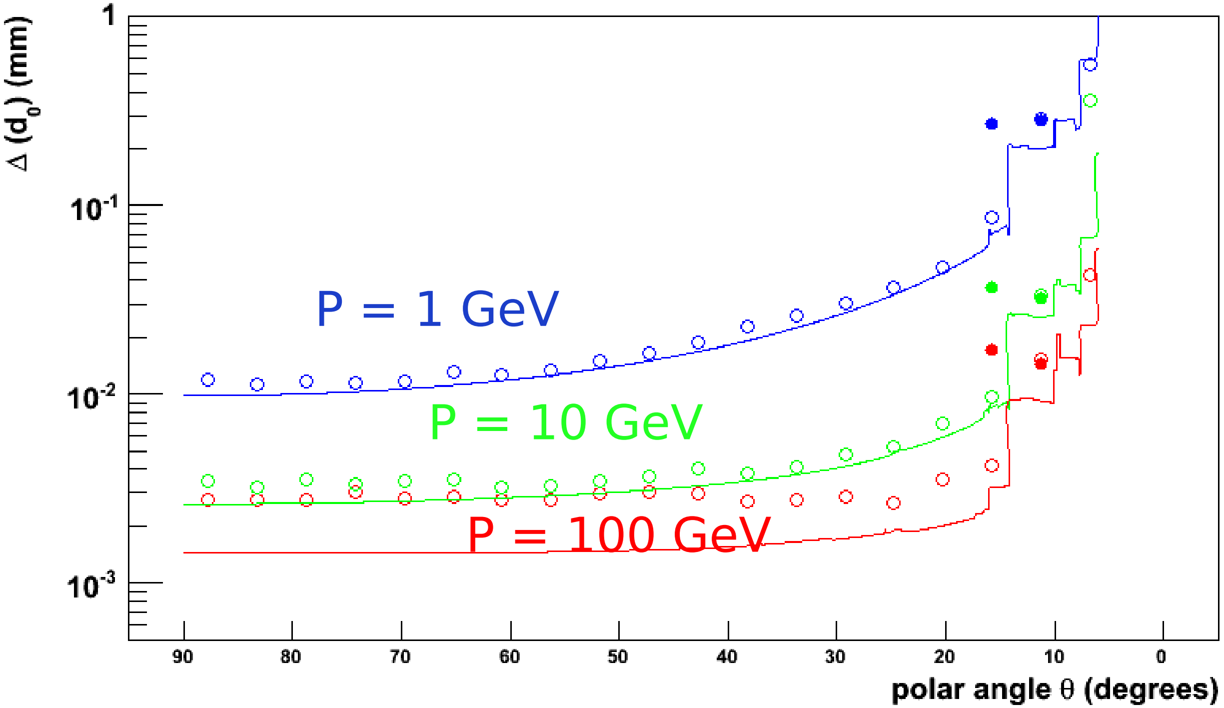
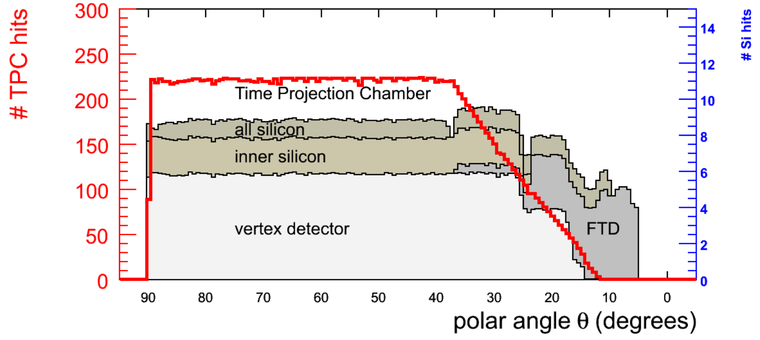


Pattern recognition



Clearly, 6-15 degrees is weakest region in ILD in terms of number of measurements. And remember:

- non-negligible pair background
- First disks close to interaction point (jets!)
- Abundant low-momentum tracks (loopers)

Ongoing study (Carmen Iglesias) Evaluate hit densities in tt events per disk and per petal (subdividing disks in 8,20 or 16 single-wafer segments)

- Average #hits/disk falls by a factor 3 due to reduced angular coverage of outermost disks
- Average #hits/petal falls even faster (outermost disks divided in 16 segments)

It is important to evaluate the hit density locally (jets)

- A significant probability to receive several hits/petal remains even in the outermost disk

	#hits/disk		#hits/petal	
disk	avg.	peak	avg.	peak
FTD1	9	37	1.1	12
FTD2	5	27	0.6	10
FTD3	8	36	0.4	10
FTD4	6	29	0.3	9
FTD5	5	25	0.3	10
FTD6	4	23	0.2	5
FTD7	3	28	0.2	4

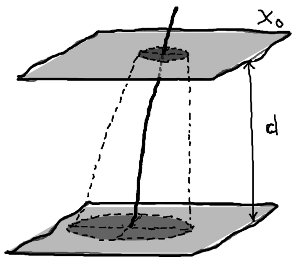
Pattern recognition - tools

Combinatorial algorithm based on KF kit

The track finder of the ATLAS (arXiv:0707:3071) and CMS (NIM A 559 143) experiments

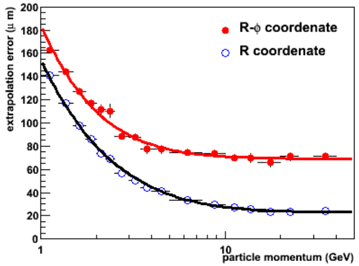
Run standalone FTD reconstruction implemented in MarlinReco processor on tt events with superposed pair background.

- Reference FTD (TESLA layout)
- 10 μm R-ϕ resolution
- 1.2 % X_0/disk (1-3) and 0.8 % X_0/disk (4-7).
- Several scenarios for R-resolution, from pixel to single-sided strip.

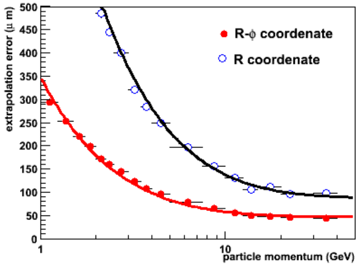


Extrapolation precision

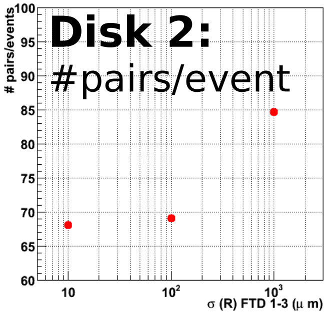
Innermost disks

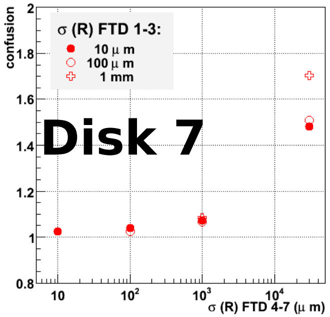


Outermost disks



Confusion





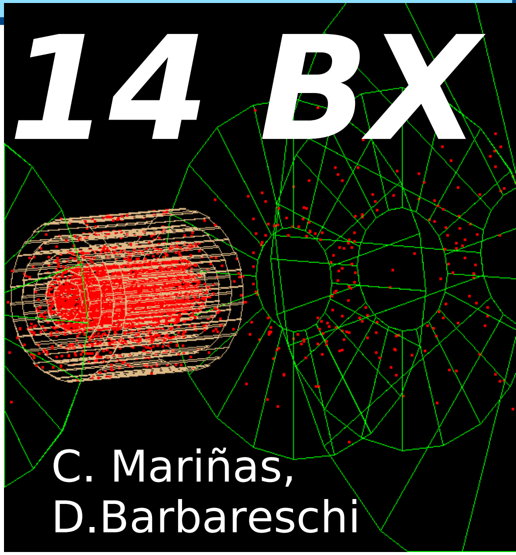
Pattern recognition

The combinatorial algorithm on stand-alone FTD is able to efficiently and cleanly reconstruct tracks down to a p_T of 100 MeV, provided:

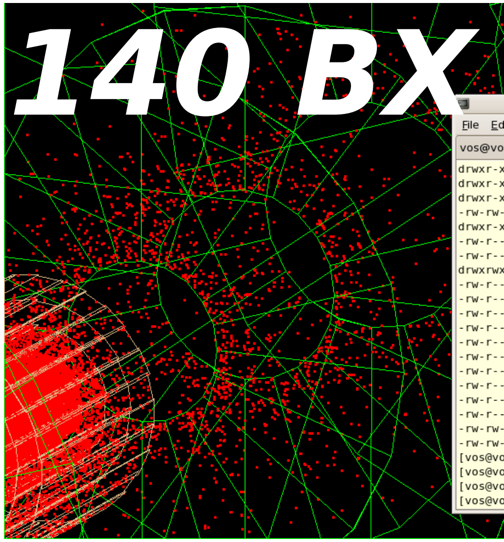
R-segmentation: in innermost disks 500 μm required, in outermost disks O (1cm)

Read-out speed: beyond several 10s of integrated bunch crossings the density of low momentum tracks prevents algorithm convergence

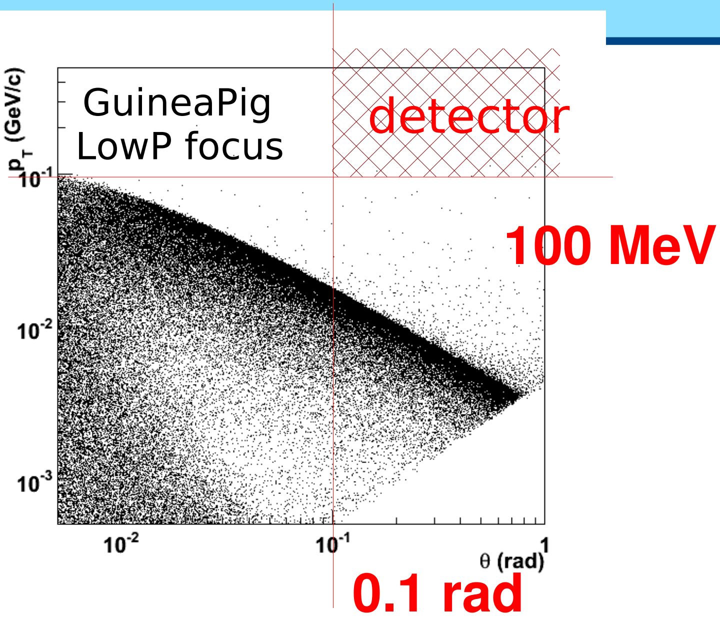
Material: an increase of the material beyond 1%/disk has dramatic consequences on pattern recognition

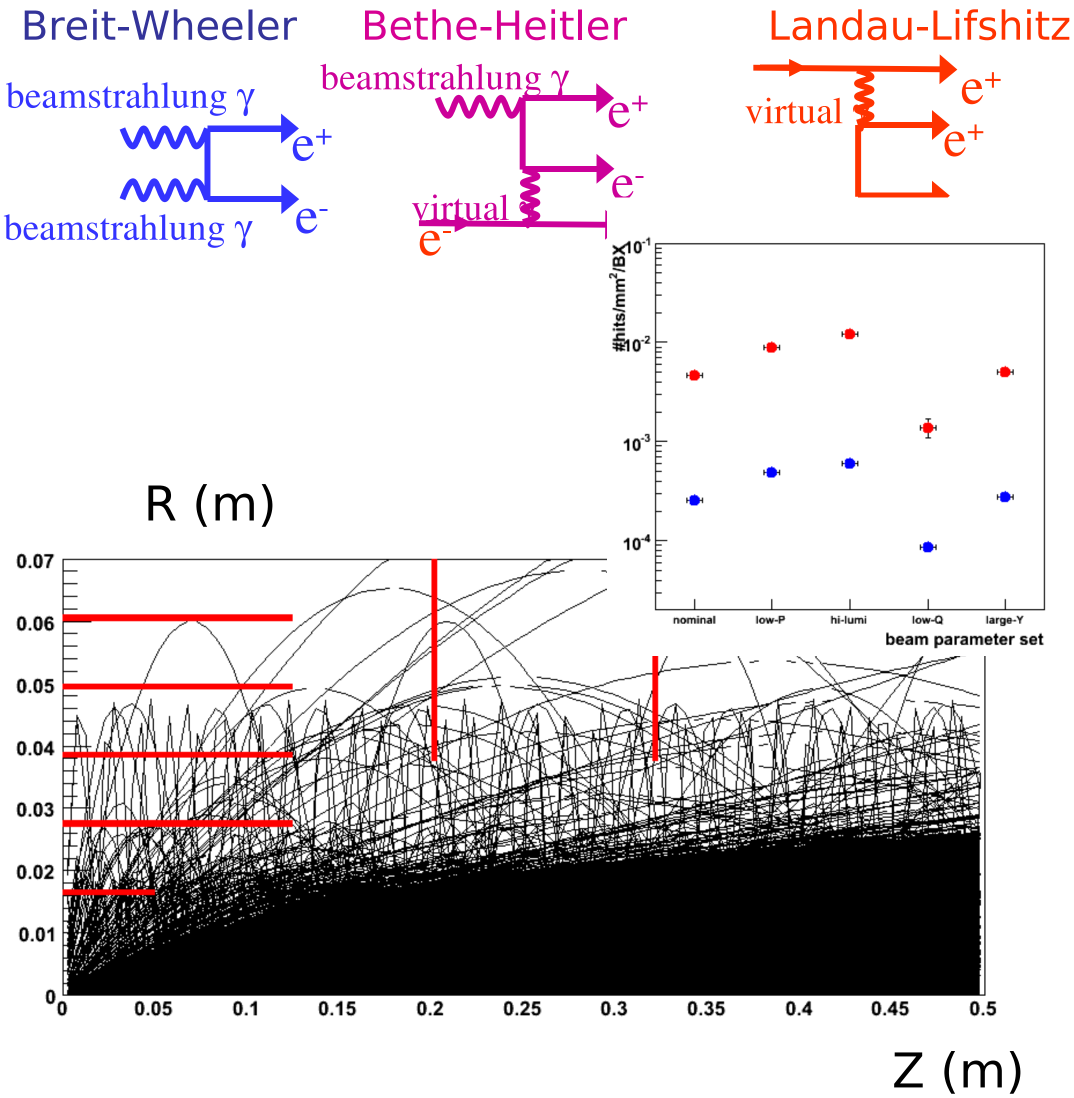


C. Mariñas, D.Barbareschi



Environment: background level





Incoherent e^+e^- pair produc off beamstrahlung photon produces a very large num of electrons and positrons each BX. The large majorit soft and/or emitted at low angle and are trapped in th "accumulation zone"

Vertex-Forward Tracking

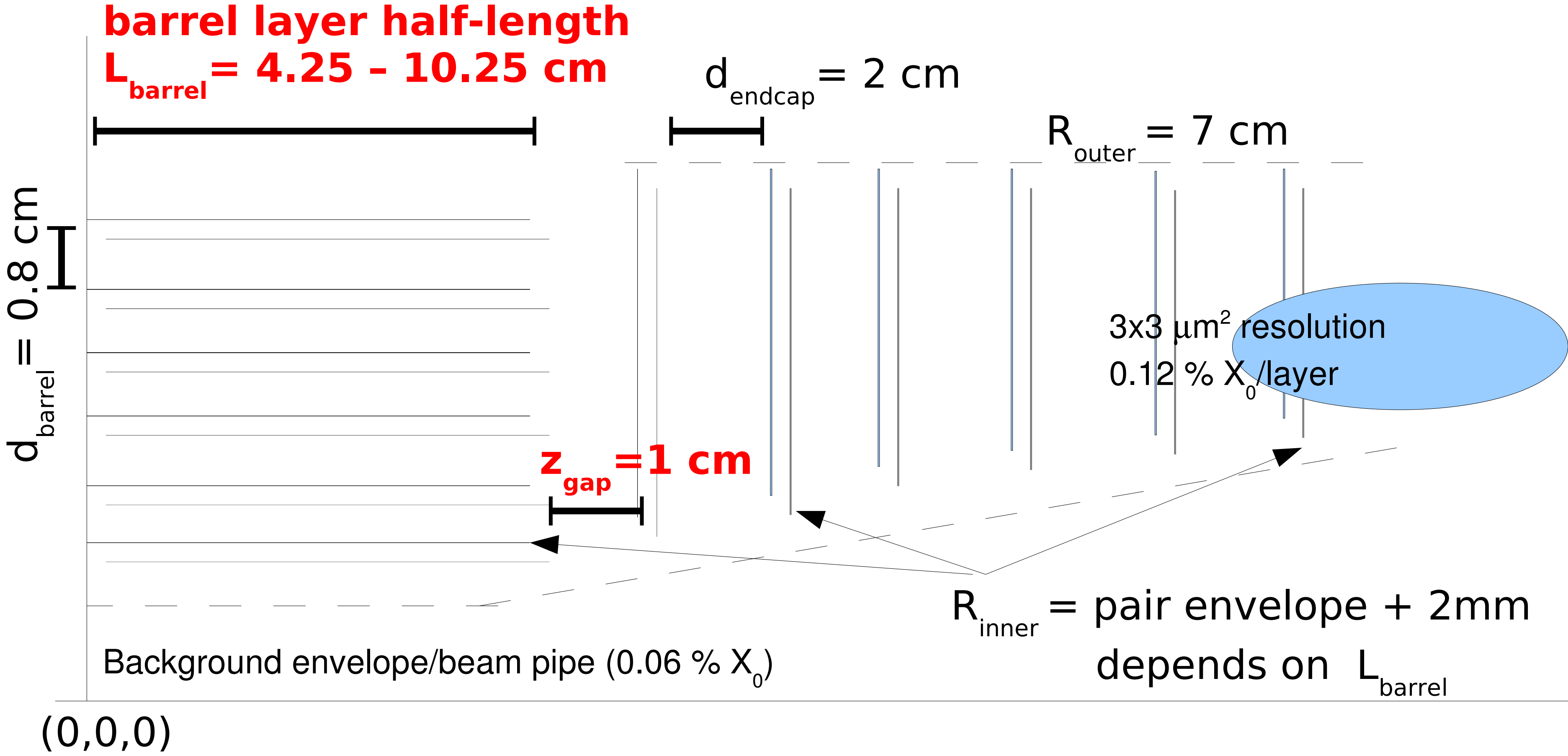
SiD (barrel+end-cap) and ILD (long barrel + FTD) have chosen very different layouts for the vertex detector and innermost forward tracking system

Establish strengths and weaknesses of different solutions by comparing the impact parameter resolution of toy geometries

CAVEAT: We're not comparing SiD and ILD (too many differences)

- Simplify the problem, reduce the number of observables
  - Vertexing is more than just flavour tagging.
  - Flavour tagging is more than just impact parameter resolution
- Simplify the problem, reduce the number of degrees of freedom
  - Uncertainty in the material budget (services!)
  - Uncertainty in the envelope of the pair background (B-field, machine parameters)
- Simplify the problem, software limitations
  - conical beam pipe (with thicker conical sections) not yet implemented

Choosing a toy geometry



barrel layer half-length

L_{barrel} = 4.25 – 10.25 cm

d_{endcap} = 2 cm

R_{outer} = 7 cm

d_{barrel} = 0.8 cm

3x3 μm^2 resolution

0.12 % X_0/layer

z_{gap} =1 cm

R_{inner} = pair envelope + 2mm

depends on L_{barrel}

Background envelope/beam pipe (0.06 % X_0)

(0,0,0)

SiD: L_{barrel} ~ 6.25 cm, z_{gap} ~ 1 cm

ILD: L_{barrel} ~ 12.5 cm, z_{gap} ~ 10 cm

Tools – track fitting

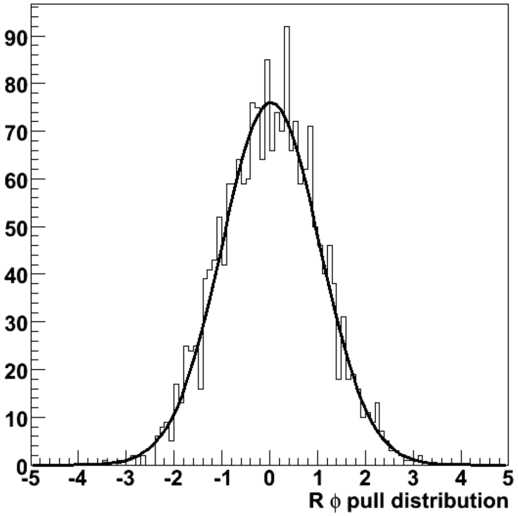
CMS Kalman filter tool-kit.

The result of years of work by a lot of people. Validated in large-scale MC productions.

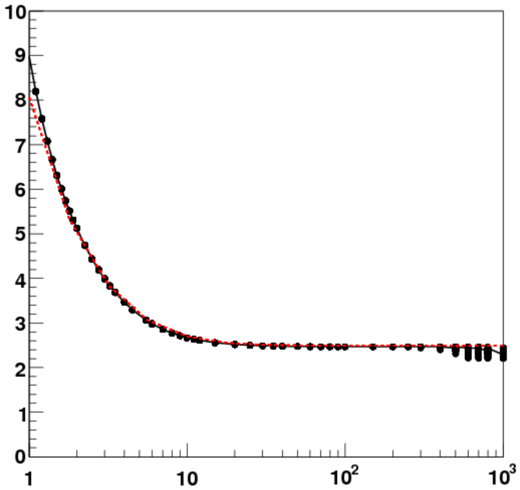
Extracted all relevant code in a series of libraries with limited external dependencies (CLHEP, ROOT).

Interfaced to toy geometries in standalone programme. Tested results for internal consistency and against existing fast-simulation packages.

Interfaced to MarlinReco (GEAR geometry, LCIO hits)



pull distribution R ϕ coordenate at last measurement plane



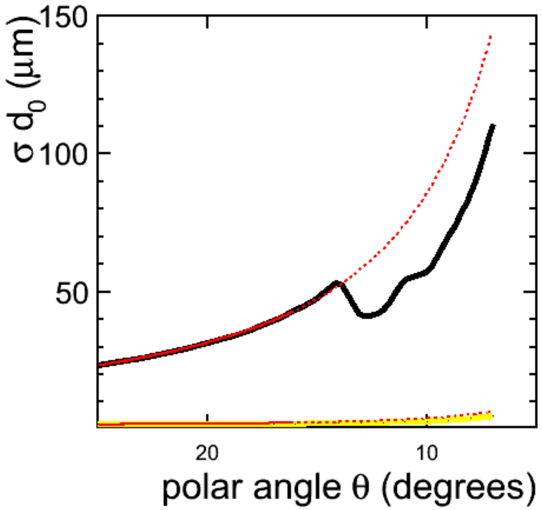
LCDTRK vs. KF: Transverse impact parameter resolution vs p_T

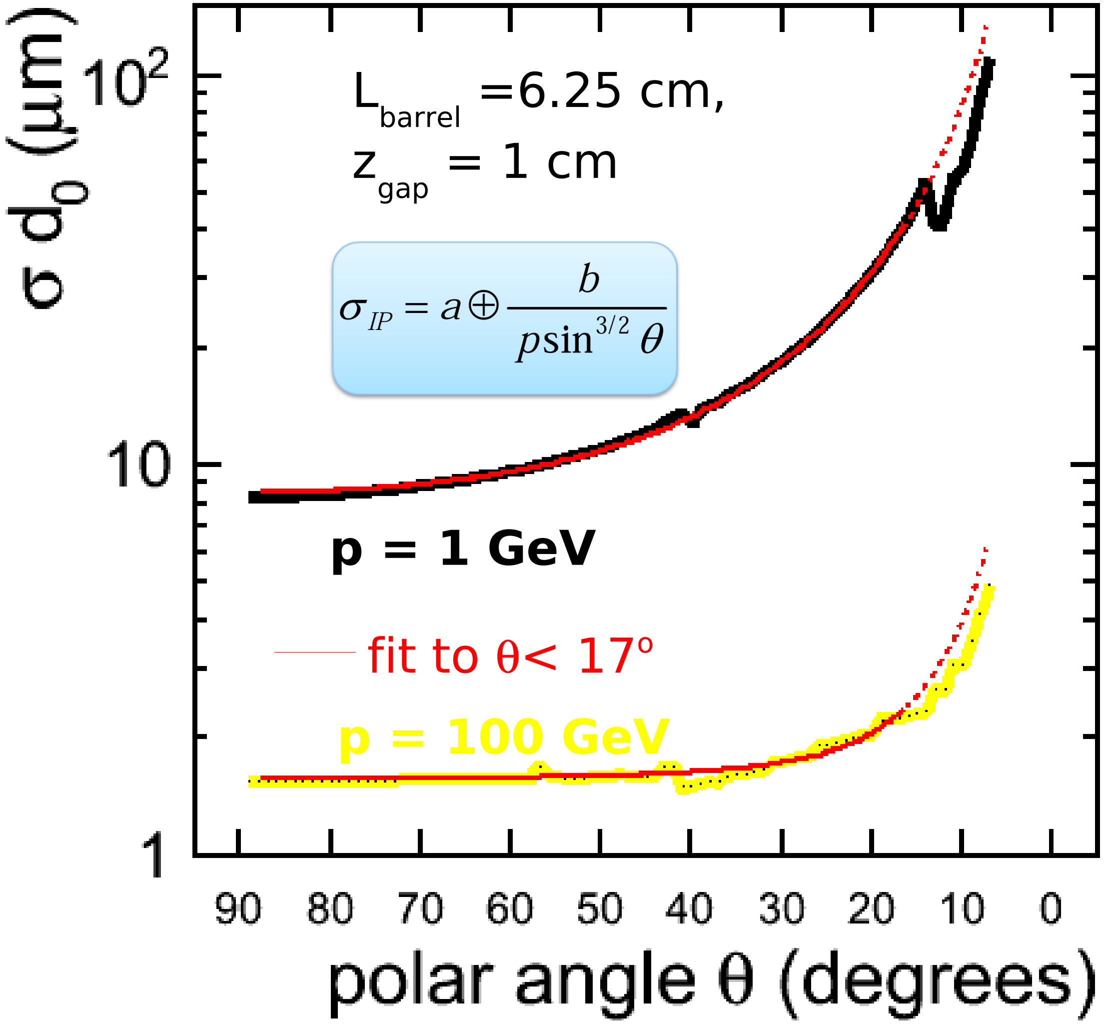
Transverse impact parameter resolution

Transverse impact parameter resolution vs. polar angle

Barrel-dominated part well-described by the standard formula.

Deviations in the very forward region (as expected)

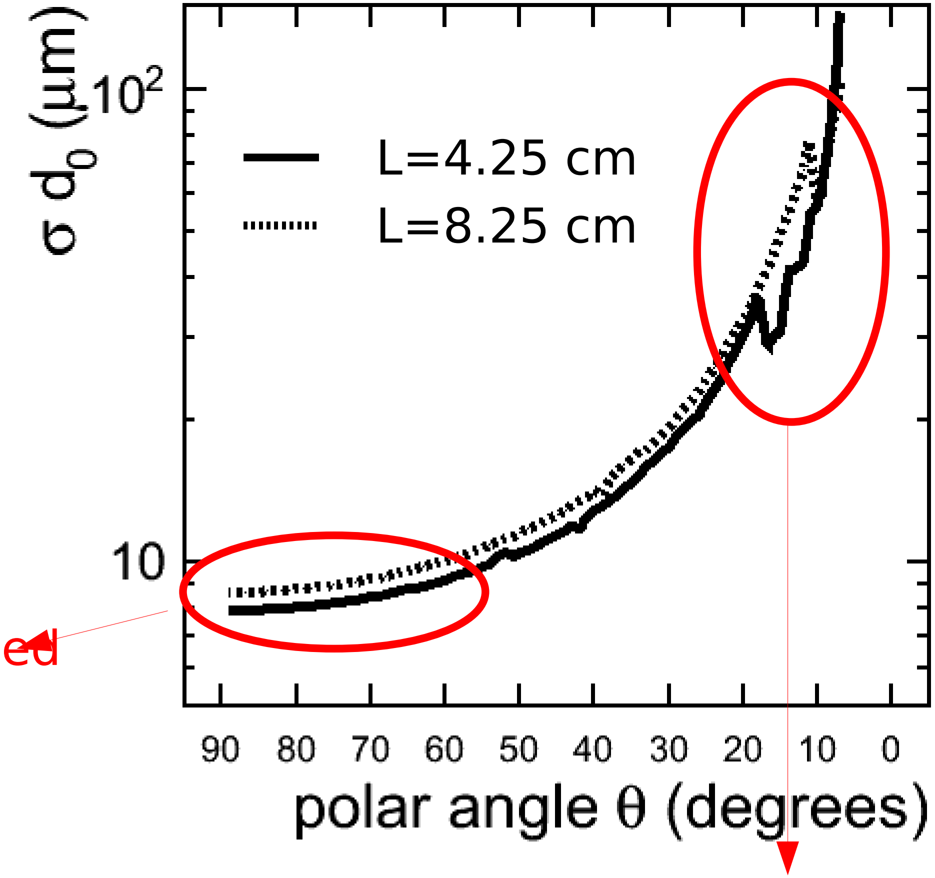




Comparison of different layouts

Longer barrel
→ worse performance

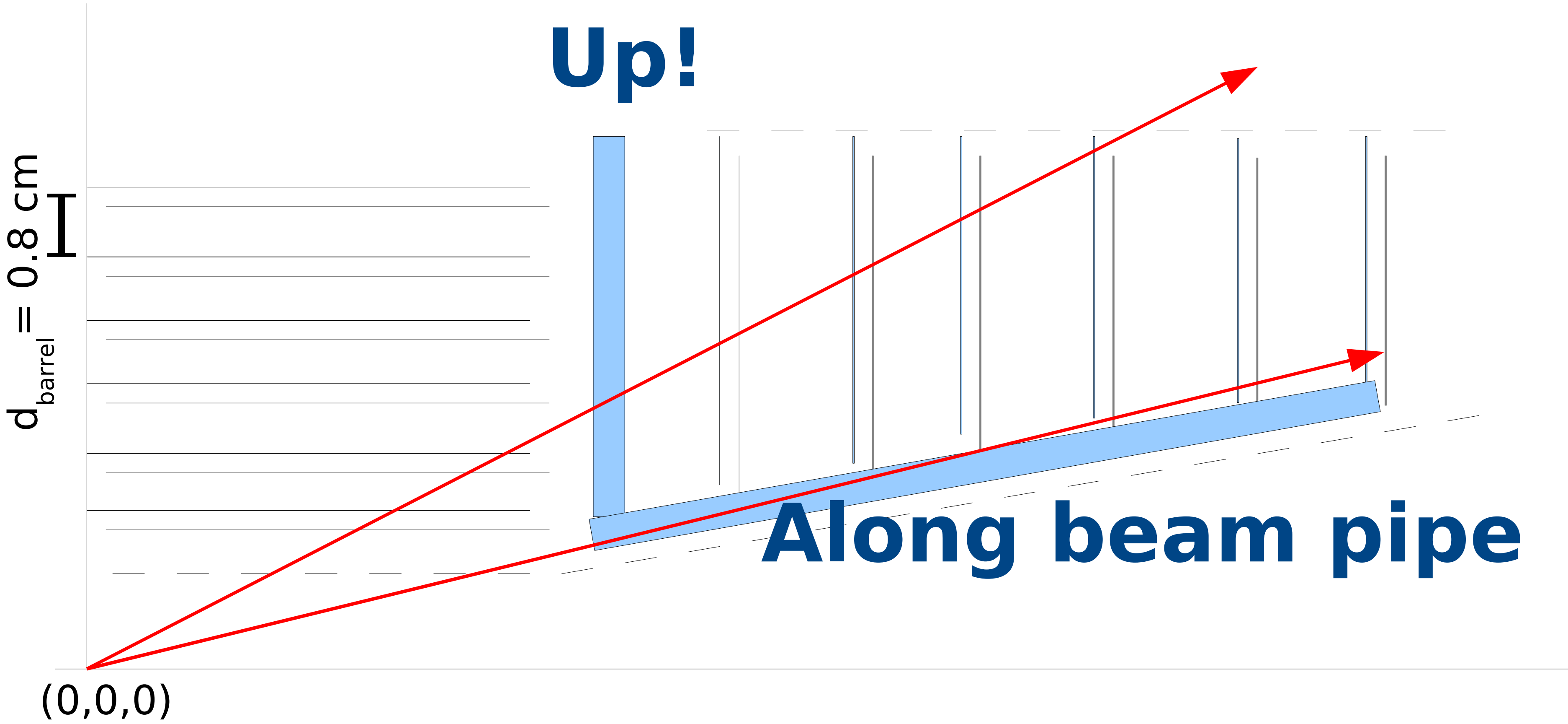
But, let's repeat with material for barrel services



Central performance degraded due to larger radius

Barrel-endcap transition moved to smaller angle

Choosing a toy geometry



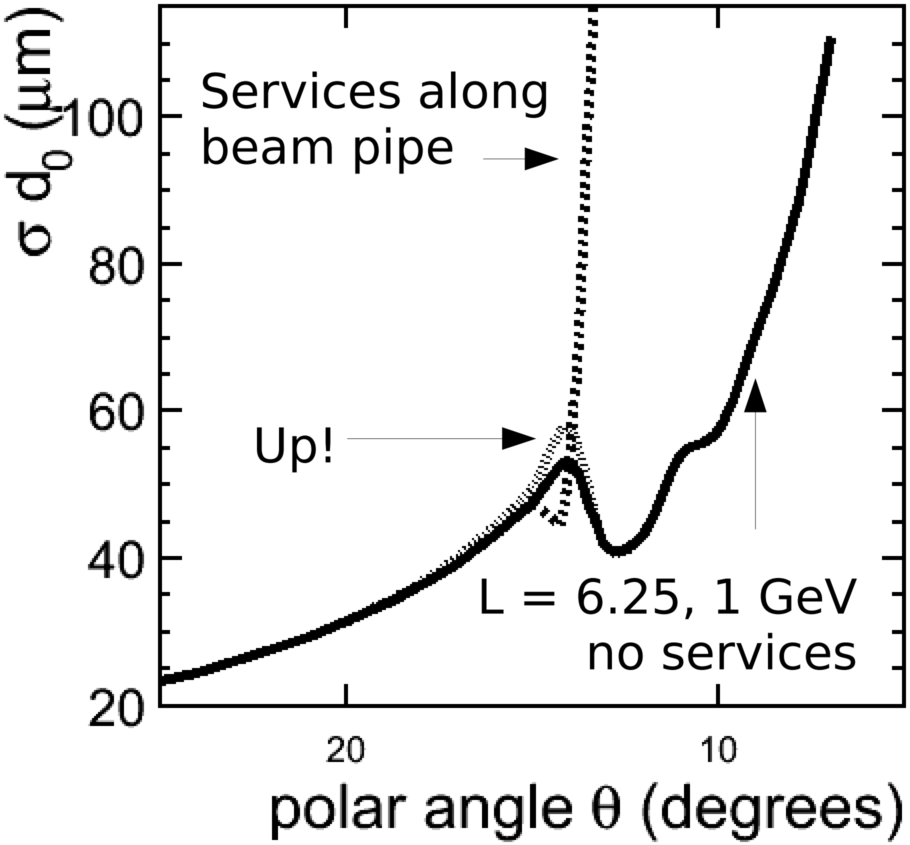
Add 3 % X_0 (on perpendicular crossing) of barrel VXD services

Two routing options

Up! or along beam pipe?

The forward region clearly does NOT like the services routed along the beam pipe

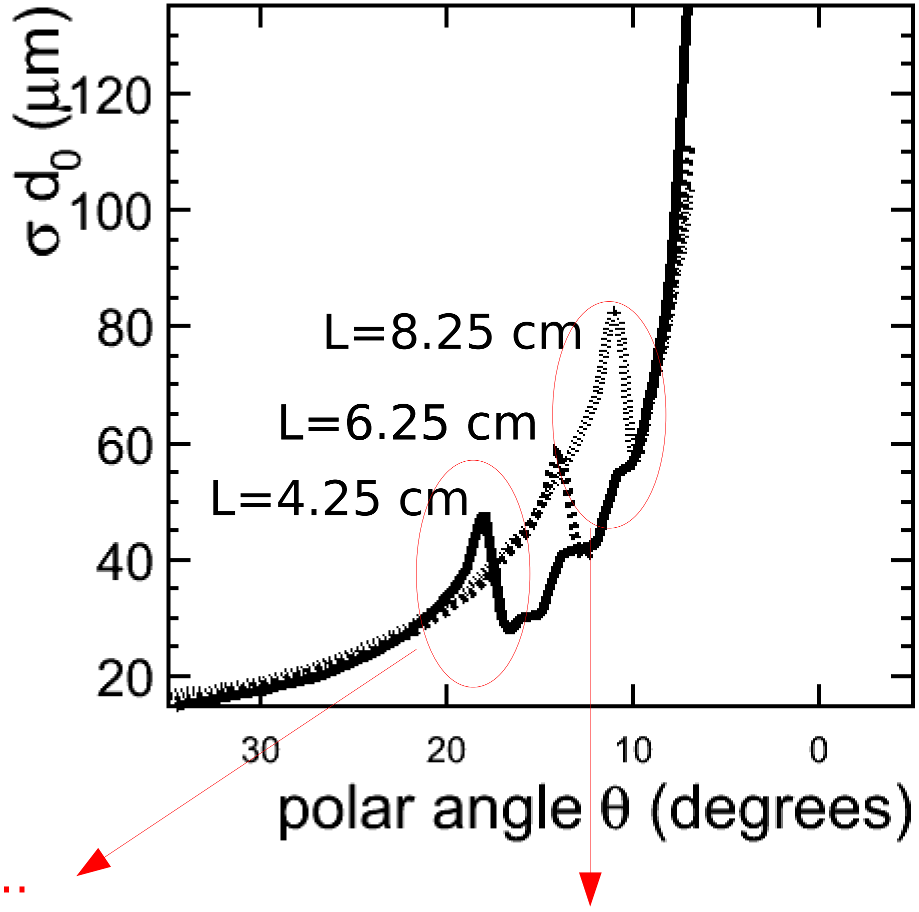
If anything close to a few radiation lengths comes in the way between endcap and interaction point we can forget about forward vertexing



Comparison L_{barrel}

A longer barrel removes the “material bump” from the central region...

Of course, the material comes back - with a vengeance – at smaller angle



Save a little here....

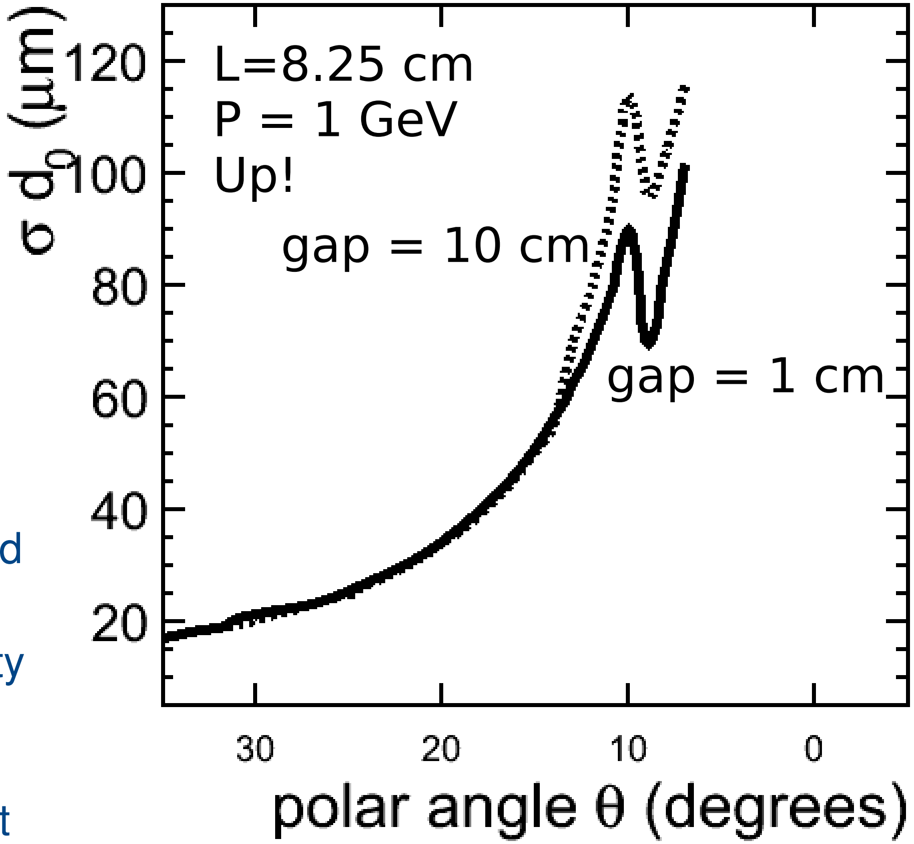
Large distance, shallow angle

Comparison z_{gap}

Minimize the gap! *

But: if we route the services along the beam pipe, the forward vertexing performance is terrible and essentially insensitive to z_{gap}

* In ILD the distance between VXD and innermost FTD is close to 10 cm. This clearance is motivated by the possibility to fit in a VXD cryostat. If a "cold" VXD technology is chosen, a short gap implies one has to install the innermost disks inside the cryostat.



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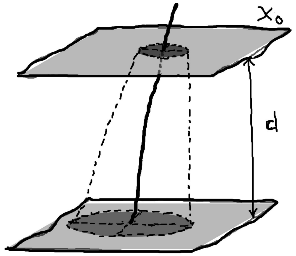
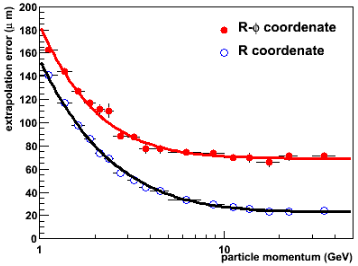
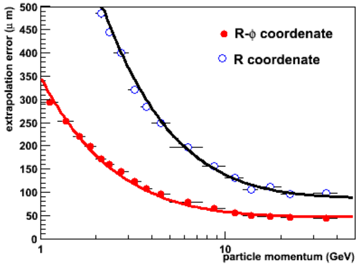


Extrapolation precision

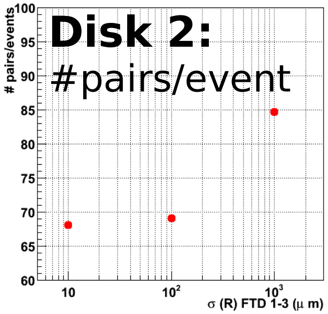
Innermost disks

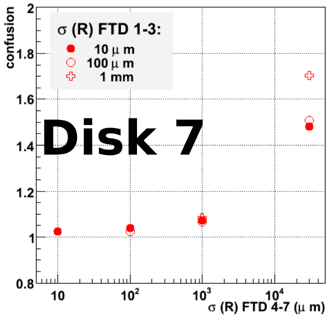


Outermost disks



Confusion


Disk 2:
#pairs/event


Disk 7